Mitigating the Impact of Mutual Interference in IEEE 802.15.4-based Wireless Body Sensor Networks

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

presented by

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Abstract

Wireless Body Sensor Networks (WBSNs) are deployed in health-related applications and their usage has rapidly increased in the past decade. Collecting various human vital signals such as heart rate or blood pressure has been made possible with the usage of WBSNs that can be implanted in or attached on the human body for monitoring and other purposes. WBSN technology can be beneficial for patients in terms of being monitored almost at all times, and signalling professional care-givers if required.

Although WBSNs have significant advantages in both medical and non-medical fields, their characteristics create quite a number of issues, including mutual interference, inefficient frequency spectrum utilisation, limited resources, communication capabilities and storage capacity, and energy constraints.

One of the most challenging issues is the mutual interference caused by neighbouring WBSNs. As the number of co-located IEEE 802.15.4-based WBSNs becomes larger in an operating frequency, their performance will be eventually influenced by the mutual interference. In fact, mutual interference eventually causes significant performance degradation due to inefficient channel utilisation.

We have investigated the impact of mutual interference on WBSN performance and a number of effective solutions is proposed to enable IEEE 802.15.4-based WBSNs to share and better utilise time- and frequency resources. More specifically, the adaptive resource allocation schemes considered in this thesis aim to improve the packet transmission reliability and to reduce the overall energy consumption in the presence of mutual interference. To accomplish this, a number of distributed schemes are proposed that step-by-step improved the packet transmission reliability and reduced the overall energy consumption. Thereafter, the sensitivity of the per-

formance of WBSNs is examined against the variation of several important system parameters for the considered schemes. This analysis has not only determined the percentage contribution of each considered system parameter to the overall performance of WBSNs, it also suggested that frequency adaptation needs to be augmented by adjusting the transmission timing of the involved WBSNs to achieve performance levels that come close to what can be achieved by an allocation computed by a centralised algorithm.

An adaptive scheme is designed and introduced that is not only able to deal with the mutual interference, but which can also be implemented on real WBSNs without substantial modifications to the IEEE 802.15.4 standard. The results obtained from both simulation-based and experimental studies have shown that the combination of both adaptive frequency hopping and adaptive phase shifting strategies can significantly improve the overall performance of WBSNs under strong mutual interference.

Publications

Related Journal and Conference Publications:

- Amirhossein Moravejosharieh and Andreas Willig. Mutual interference in large populations of co-located IEEE 802.15.4 body sensor networks - A sensitivity analysis. Computer Communications, 2016. ISSN 0140-3664. doi: http://dx.doi.org/10.1016/j.comcom.2016.01.002.

- Amirhossein Moravejosharieh and Jaime Lloret. Performance evaluation of co-located IEEE 802.15.4-based wireless body sensor networks. Annals of Telecommunications, 2016. Accepted.

- Amirhossein Moravejosharieh and Jaime Lloret. A survey of IEEE 802.15.4 effective system parameters for wireless body sensor networks. International Journal of Communication Systems, 2015, doi: 10.1002/dac.3098, ISSN 1099-1131.

- A. Moravejosharieh, E.T. Yazdi, K. Pawlikowski, and H. Sirisena. Adaptive channel utilisation in IEEE 802.15.4 wireless body sensor networks: Adaptive phase-shifting approach. In International Telecommunication Networks and Applications Conference (ITNAC), Nov 2015.

- A. Moravejosharieh, A. Willig, and K. Pawlikowski. Frequency-adaptive approach in IEEE 802.15.4 wireless body sensor networks:Continuous- Assessment or Periodic-Assessment? Australasian Journal of Information, Communication Technology and Applications, 1(1), 2015.

- A. Moravejosharieh, E.T. Yazdi, A. Willig, and K. Pawlikowski. Adaptive channel utilisation in IEEE 802.15.4 wireless body sensor networks: Continuous hopping approach. In Australasian Telecommunication Networks and Applications Conference (ATNAC), doi:10.1109/ATNAC.2014.7020880, pages 93-98, Nov 2014,

- Amirhossein Moravejosharieh and Ehsan Tabatabaei Yazdi. Study of Resource Utilization in IEEE 802.15.4 Wireless Body Sensor Network, Part I: The Need for Enhancement. In IEEE 16th International Conference on Computational Science and Engineering (CSE), pages 1226-1231, December 2013.

- Amirhossein Moravejosharieh, Ehsan Tabatabaei Yazdi, and Andreas Willig. Study of resource utilization in IEEE 802.15.4 Wireless Body Sensor Network, Part II: Greedy Channel Utilization. In 19th IEEE International Conference on Networks (ICON), pages 1-6, December 2013.

Other Publications:

- Yazdi, E.T. and Moravejosharieh, A. and Willig, A. and Pawlikowski, K., "Coupling Power and Frequency Adaptation for Interference Mitigation in IEEE 802.15.4 Based Mobile Body Sensor Networks: Part II", In *2014 IEEE International Conference on Australasian Telecommunication Networks and Applications Conference (ATNAC)*, 2014.

- Yazdi, E.T. and Moravejosharieh, A. and Kumar Ray, S., "Study of Target Tracking and Handover in Mobile Wireless Sensor Network", In *IEEE* 28^{th} *International Conference on Information Networking (ICOIN)*, pages 120-125, 10^{th} of February 2014.

Dedications

To my beloved parents Dr. Mohammad Mehdi Moravejosharieh and Mrs. Marzieh Raeesi, for their great support, continuous generosity and encouragement throughout my entire life, and to my lovely sisters Somayeh and Reihaneh Moravejosharieh and their families who are always there for me:
It is with my deepest gratitude and warmest affection that I dedicate this thesis to you all, without whom none of my success would be possible.

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Chapter 2: Background and Literature Review

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List of Abbreviations

AMPE Adaptive MAC for Efficient low-power communication

BE Back-off Exponent

BI Beacon Interval

BO Beacon Order

BOAA Beacon Order Adaptation Algorithm

CA Continuous Assessment

CAP Contention Access Period

CCA Clear Channel Assessment

CFP Contention Free Period

CMAC multi-Channel MAC

CR Cognitive Radio

CSMA Carrier Sense Multiple Access

CSMA-CA Carrier Sense Multiple Access with Collision Avoidance

CTS Clear To Send

CW Contention Window

DCA Dynamic Channel Allocation

DCA Duty Cycle Algorithm

DCLA Duty Cycle Learning Algorithm

DCM Dynamic Coexistence Management

DMMAC Dynamic Multi-radio Multi-channel MAC

DPS Dynamic Phase Shifting

DSSS Direct Sequence Spread Spectrum

DYMO Dynamic Manet On demand

ED Energy Detection

EGG ElectroCardioGram

FFD Full Function Device

GTS Guaranteed Time Slot

HBC Human Body Communications

ISM Industrial Scientific and Medical

LIB Linear Increase Back-off

LQI Link Quality Indicator

LR-WPAN Low-Rate Wireless Personal Area Network

MICS Medical Implant Communication Service

NB Number of Back-off

NePSing Network Protocol Simulator

NEVS Nearest Vacancy Search

NS-2 Network Simulator version 2

O-QPSK Offset Quadrature Phase-shift Keying

OMNET Object-oriented Modular Network Simulator

OPNET Optimised Network Engineering Tool

P-to-P Peer-to-Peer

PA Periodic Assessment

PER Packet Error Rate

PHY Physical

PLME-CCA Physical Layer Management Entity - Clear Channel Assessment

PU Primary User

QoS Quality of Service

RF Radio Frequency

RFD Reduced Function Device

RSM Response Surface Methodology

RSSI Received Signal Strength Indication

RTS Request To Send

RX Receive

SABT Superframe Adjustment and Beacon Transmission

SD super-frame Duration

SO Superframe Order

SUTE Scheduler Using Throughput Estimator

TDMA Time Division Multiple Access

TX Transmit

UWB Ultra-Wide-Band

WBAN Wireless Body Area Network

WBSN Wireless Body Sensor Network

WiFi Wireless Fidelity

WSN Wireless Sensor Network

1 Introduction

In this chapter, a set of arguments is established indicating the main purpose of conducting this research. First, an overview of a Wireless Sensor Network (WSN) is provided followed by a brief description of a Wireless Body Sensor Network (WBSN) and the main differences between them. Next, the “problem statement” is presented to address an important shortcoming of one the standard protocol being deployed in WBSNs and the proposed solutions and approaches are discussed thereafter. Finally, the methodology is described including the considered performance measures, hypotheses and contributions of this thesis followed by the outline of this thesis.

1.1 Wireless Sensor Networks

Advances in microelectronic devices such as tiny microprocessors and low-power radio technologies have provided the opportunity of creating low-cost, low-power and multifunctional sensor devices. Such sensors are used to observe the surrounding environment, collect certain information and take proper actions on it. WSNs based on the IEEE 802.15.4 standard is expected to play a key role in a diverse set of applications, e.g. medical [4, 70], agriculture, environment monitoring, surveillance, military, sports [38, 69] and entertainment. For example, in the medical field, a WSN attached to a body to collect vital signals can provide professionals with the opportunity to remotely monitor the medical condition of a patient such as blood pressure, heartbeat or even blood sugar. The gathered information can be transmitted to professionals either periodically or on event-detection basis [92], [93], [112], [23], [41] and [72].

A typical wireless sensor network consists of many sensor nodes that are wirelessly connected to each other, forming a network. Each sensor node interacts with other nodes and takes its part in fulfilling the duty of the sensor network as a whole. The role of each sensor node may vary based on its type, expected functionality and the deployed protocols. For instance, a sensor node can be a full-function device such as a base-station or a reduced-function device such as a typical sensor device which is responsible to measure signals from the surrounding environment. A sensor node is comprised of several components connected to each other. It contains a micro-controller, wireless transceiver, power source, sensors and/or actuators. The size of wireless sensor networks is quite variable and can vary from a few to thousands of nodes, depending on the requirement of the application. The application and the deployed protocol dictate the topology of the sensor networks: single-hop *star* topology or multi-hop *mesh* topologies. There are some constraints and challenges that need to be carefully considered while designing and developing a wireless sensor networks e.g. energy consumption, reliability, timeliness, robustness, mobility and fault tolerance. These challenges can be prioritised based on the requirement of the applications and protocols.

1.2 Wireless Body Sensor Networks

WBSNs are mainly considered for health-related and well-being, entertainment and tracking applications [15, 19, 60, 114]. The focus of this research is on health-related applications in which the crucial factors are the reliability and timeliness of successful data transmission between sensor nodes. More specifically, in health-related applications the sensor nodes are attached to human body, collect human body vital signals and either directly or indirectly transmit the collected information to professionals thereafter. These applications are highly useful to monitor the health status of those who need constant supervision while allowing them to have their independence and freedom.

Although WBSNs have many characteristics in common with classic WSNs, the key differences are their relatively small size (both in number of sensors and the network diameter) and the mobility feature of networks as a whole. In a typical WBSN, sensor nodes transmit the collected information to a central unit called coordinator that is one or at most two hops away from them. The most commonly used topology for such sensor networks is the single-hop star topology [27, 43].

There are many protocols and standards offered for WSNs and WBSNs [2, 3, 55, 58]. The IEEE 802.15.6 standard [2] is specifically designed for WBSNs and has been recently standardised and released. However, we have not considered this standard as to the best of the author's knowledge, no sensor nodes following the specifications of this standard were commercially available at time of conducting this research.

IEEE 802.15.4 is considered as a mature and well-established standard protocol that is also interesting for WBSNs [58]. This standard describes a Low-Rate Wireless Personal Area Network (LR-WPAN) and is designed to offer simplicity and reduce the network communication costs. This protocol supports the MAC and the PHY layers and its specifications is limited to these layers only. Due to the commercial availability of IEEE 802.15.4 compliant component and its simplicity, this protocol is expected to remain a serious contender for wireless sensor networks and wireless body sensor networks, at least for quite some time in future. Therefore, we have considered this standard protocol as the benchmark protocol and further enhancements are assessed against this standard.

The physical layer offered in the IEEE 802.15.4 protocol supports a total of 27 different operating frequencies or channels. Amongst these, 16 channels are in the 2.4 GHz Industrial Scientific and Medical (ISM) band. This frequency band is arguably the most popular frequency band utilised by IEEE 802.15.4-based technologies. It is also utilised by other technologies such as Wireless Fidelity (WiFi) and Bluetooth. The coexistence of wireless body sensor networks with other technologies is beyond the scope of this thesis [121]. In this thesis we are interested to study the coexistence of several IEEE 802.15.4-based WBSNs and evaluate their performance gains as the number of them becomes larger in the 2.4 GHz frequency spectrum.

1.3 Problem statement

As mentioned earlier, energy consumption, reliability, timeliness, robustness, mobility and fault tolerance are considered as important requirements while designing and developing wireless sensor networks. However, some of these requirements could be given more priority compared to others based on the application necessities. Since WBSN applications mostly deal with human body vital signals, data packet transmission reliability, timeliness and sensor node's energy consumption are considered as the most important requirements for these applications. It is crucial to establish and maintain timely and reliable data transmission between a sensor node and a coordinator node in a WBSN. Sometimes loosing information related to human body vital signals or receiving it with long delay could cost a life. For instance, it might be essential to constantly monitor a patient's vital signals when hiring a caregiver is not an option or when a patient needs freedom to do his routine activities. In such scenarios, WBSN can provide constant monitoring of patient's health status with low cost and low maintenance.

One of the major issues with IEEE 802.15.4-based WBSNs is *interference* caused by sharing the same frequency spectrum with the same or other technologies. The interference caused by WSBNs of the same technology over each other is preferably called **internal** or **mutual** interference, whereas the interference caused by different technologies is called **external** interference. In this thesis we entirely focus on mutual interference and the terms internal and mutual are used interchangeably.

We consider scenarios where a large number of people wearing wireless body sensor networks gather at the same place, for instance sport events or emergency hospitals, and we assess the impact of mutual interference on their packet transmission reliability.

Within a typical WBSN, a sensor node periodically transmits the collected data to its associated coordinator node during a confined and specific time called the "active period". Once the transmission is successfully completed, the sensor node sleeps to save energy. As the number of WBSNs in a channel becomes larger, the overlapping ratio of their active periods will increase. As a result, WBSNs experience noticeable data transmission failure rates, which eventually leads to significant performance degradation [82], [83], [50], [35], [36] and [34]. In order to study and assess the impact of "internal interference", we did not consider any other technology in our research. This means that the 2.4 GHz frequency spectrum is entirely assigned to IEEE 802.15.4-based wireless body sensor networks. We have classified the channel utilisation into three – white, grey and red – regions, which represent if a particular point in time on a particular channel is idle, being used by one user or being used by two or more neighbouring wireless body sensor networks, whose active periods overlap on each other, respectively. Figure 2.5 represents a possible channel utilisation of several wireless body sensor networks and the mentioned classifications.

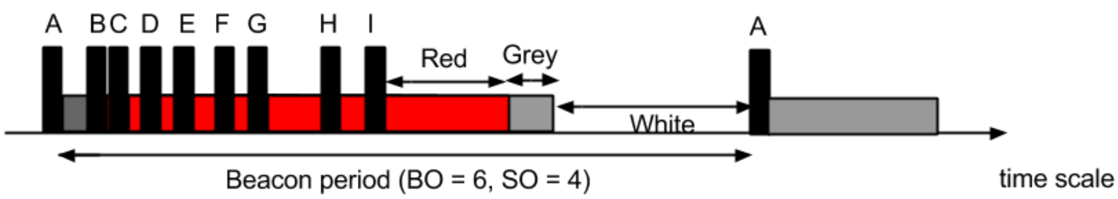


Figure 1.1: The channel utilisation characteristics

Clearly, as the number of wireless sensor networks becomes larger in a channel the "red" region becomes larger, which indicates a higher probability of packet collisions and eventually performance degradation. The "white" region in Figure 1.1 indicates the point of time that is not used by any of the active WBSNs in that channel and is interpreted as "inefficient" channel utilisation. In other words, inefficient channel utilisation means that the performance degradation, as a result of overlapping active periods, occurs while WBSNs are not utilising the available free time slots in a channel. The IEEE 802.15.4 standard protocol does not offer an efficient channel utilisation method, and therefore, wireless body sensor networks that are using this standard protocol will eventually experience performance degradation as a result of mutual interference.

Another important requirement in WBSNs is the "overall network life time". Since WBSNs use batteries as their source of energy, **energy consumption** is one of the major constrains for sensor networks. Within a sensor node, a large portion of energy is consumed by the radio transceiver [48]. As the number of WBSNs in the channel becomes larger, mutual interference causes packet collisions and eventually packet losses. Generally, packet collisions result in higher energy consumption in two ways: data packet re-transmissions, and turning an associated sensor node to an *orphan* (a node that has lost connection and synchronisation with its corresponding coordinator). Clearly, re-transmission of data packets requires using the radio transceiver and consumes additional energy. Becoming an orphan means that the sensor node needs to listen to a subset of channels to find its corresponding coordinator node and this requires using its radio transceiver, and thus higher energy consumption. Additionally, an orphan sensor node is not able to transmit the collected data to its attached coordinator and this results in delays and data packet losses (due to discarding data packets from the buffer).

Currently, a typical IEEE 802.15.4-based WBSN is not able to avoid the mutual interference caused by neighbouring wireless body sensor networks operating in the same channel. Therefore, it would be beneficial for a WBSN to deploy mechanisms to measure its surroundings and become "adaptive" against mutual interference, e.g. by adjusting operational parameters to avoid mutual interference and/or to mitigate its destructive impacts on a WBSN's performance gains.

As previously-mentioned, IEEE 802.15.4 standard protocol covers both physical and MAC layers. On the physical layer, one of the main adjustable parameters is the *operating frequency* (channel). This layer also offers various metrics to assess the channel quality such as Received Signal Strength Indication (RSSI), Energy Detection (ED) and Link Quality Indicator (LQI). These metrics are useful when WBSNs deal with the external interference (due to the different nature of channel utilisation). However, considering the homogeneous WBSN where all nodes utilise the active and inactive – nodes sleep to save energy – structure, the nature of the network load does not show the bursting behaviour. Therefore, the offered approaches for channel quality assessment are not beneficial to utilise for homogeneous WBSNs. In this thesis we proposed a method to collect the necessary information about the occupancy-level of different channel. The proposed method also enables a WBSN to collect information about the duty cycle of other WBSNs, while the information provided by RSSI, ED and LQI metrics is limited to energy-level of the channel.

On the MAC layer, the IEEE 802.15.4 standard protocol offers two operation modes: beacon-enabled mode and non-beacon-enabled mode. Two different approaches are supported by the MAC layer to provide access to the channel for the sensor nodes: Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) approaches. Please note that the TDMA approach is utilised in a specific duration of time within an active period called Guaranteed Time Slot (GTS) to eliminate the interference caused by sensor nodes within a body sensor network. However, it has been shown in [121] that the lack of carrier-sensing in TDMA time slots in the presence of interference results in significant WBSN performance degradation.

In this thesis, we mainly focus on challenges and issues caused by mutual interference and its destructive impacts on data packet transmission reliability, timeliness and node‘s energy consumption. The main goal of this research is to investigate the feasibility of different approaches for **mutual interference avoidance ap-**

proaches in particular adaptive and collaborative resource allocation for WBSNs. The performance of these approaches is then evaluated against the IEEE 802.15.4 standard protocol's performance both by simulation-based and experimental studies. Additionally, we determine the influence of a candidate set of important system parameters (mostly MAC parameters) on the performance of the WBSNs in the presence mutual interference, for all proposed approaches.

1.4 Proposed solution

One of the possible approaches to mitigate the impact of the mutual interference is to avoid channels with a large number of occupants. Another possible approach is to shift to another time slot / phase to avoid the overlapping of the own active period with its neighbour's as much as possible. To accomplish this, a WBSN is required to do the followings:

- **Spectrum scanning procedure:** As mentioned earlier, the channel quality assessment metrics offered in IEEE 802.15.4 standard protocol are not ideal for homogeneous scenarios. Therefore, a heuristic *spectrum scanning procedure* is proposed to find a potentially suitable operating frequency. This procedure provides a WBSN with an opportunity of selecting a channel with the smallest number of occupants and in which less active period overlapping is expected to occur. Selecting such a channel requires scanning all available channels. This scanning procedure can be performed at the very initial stage of a WBSN's activation or can be performed continuously throughout. In this thesis we assume that coordinators – as an entity which is responsible to perform the spectrum scanning procedure – can be equipped with higher capacity batteries and their energy consumption is not as crucial as sensors. On one hand, scanning the frequency spectrum results in higher energy consumption and on the other hand such channel promises lower levels of mutual interference. An important question is *how often* the spectrum scanning procedure should be performed. Therefore, two periodically different ways of spectrum scanning procedures are considered in this thesis: **periodic** spectrum scanning, and **continuous** spectrum scanning. With the periodic spectrum scanning the frequency spectrum is scanned periodically, which consumes less energy compared to continuous spectrum scanning. However, the latter approach provides the most up-to-date information regarding the number of occupants of each channel compared to the first one, due to continuously scanning the frequency spectrum and tracking the channel with the smallest number of occupants.

- **Network performance assessment:** Since a specific network performance assessment mechanism is not defined in the IEEE 802.15.4 standard, we have designed a heuristic algorithm to enable WBSNs to assess their performance whenever it is required. To accomplish this, the coordinator of a WBSN assesses the performance of its network through counting the number of packet losses.

- **Channel switching procedure:** This procedure allows a WBSN to switch to another operating frequency when its performance has degraded below a threshold. The new channel can be determined either randomly or using the information provided by spectrum scanning procedure. According to the latter approach, a WBSN switches to the channel with the smallest number of occupants hoping to experience lower active period's overlapping ratio compared to the random selection of a channel, where there is a possibility that the WBSN switches to a channel with a larger number of occupants and experiences an even higher overlapping ratio. Switching to the channel with the smallest number of occupants benefits from the most up-to-date information provided by the continuous spectrum scanning offered in spectrum scanning procedure.

- **Phase shifting procedure:** This procedure allows a WBSN to change its active phase / time slot within the current channel, whenever its network's performance has degraded below a threshold. The new phase (to shift to) can be determined either randomly or by using specialised algorithms to find gaps in the channel and shift the phase to fill such gaps. In this thesis, the new phase is determined using a random shifting strategy to avoid introducing high complexity to the system.

  To shift to a new phase, a WBSN simply picks a real random (uniform distribution) number selecting from (0, length of a beacon period) as the future time slot/phase and shifts its beacon packet to that time slot, thereafter. Moreover, WBSNs are able to communicate with each other To find the channel with the smallest number of occupants. To accomplish this, the coordinator of a WBSN always listens to the channel, detects as many other beacon packets as possible, includes this information to its beacon packet and transmits it, periodically. This way a WBSN (more particularly the coordinator) has the information related to the occupancy-level of all channel and can switch to the channel with the smallest number of occupants and perform the phase shifting procedure if required[1]. This allows the coordinator of a WBSN to have more accurate estimation about the number of occupants of other channels when performing the spectrum scanning procedure. Please note that selecting a future time slot/phase in a random manner is envisaged to create a simple approach witch is compatible with IEEE 802.15.4 standard MAC and to avoid any modifications to this standard.

Continuously scanning the frequency spectrum and actively switching to the channel with the smallest number of occupants can be an effective solution to avoid mutual interference. However, the capability of shifting beacons to other time

[1] A certain condition has to be met for switching to the channel with the smallest number of occupants. This condition is considered to prevent multiple WBSNs switch to the same channel with the smallest number of occupants.

slot/phase within a channel combined with the channel-switching (channel-hopping) strategy can be a promising approach to avoid the mutual interference. In order to achieve a clear view on the impact of mutual interference, series of analysis are carried out in scenarios that are not disturbed by other effective parameters such as hidden-terminal situations, external interference, fading channels, path loss and different transmit power settings. Therefore, all WBSNs are configured to have the same transmit power and are located at the same spot.

A range of schemes is investigated in which the above-mentioned procedures are utilised in different combinations. For each considered scheme, the WBSN performance is obtained using a range of system parameters by conducting simulation studies. In particular, we have not only assessed selected parameters combinations, but also we have systematically assessed the relative impact of the selected parameters. This sensitivity analysis allows to determine the most influential system parameters on a WBSN's performance.

In this thesis we are more interested in applications that have notion of *acceptable* and *unacceptable* performance, e.g. in terms of packet losses for regularly transmitted sensor signals. Clearly, in such applications a certain threshold must be defined as a requirement to distinguish acceptable performance from the unacceptable one.

In this thesis we study the following questions:

How can a large group of WBSNs share the same frequency spectrum in such a way that only small percentage of them experiences performance degradation below the predefined threshold?

and

For a given proposed scheme, what are the most influential system parameters on WBSN performance?

and

How does the impact-intensity-level of each parameter vary as the mutual interference becomes more intense?

and

Is it feasible to implement the scheme (that has achieved the highest performance in the simulation-based study) on the real-world sensor devices? Is it possible to qualitatively confirm the outcome of experimental study by comparing it to the simulation-based study?

1.5 Methodology and Contributions

This research aims to achieve a set of objectives where the main goal is to improve the reliability and timeliness of packet transmission and to reduce the sensor node's energy consumption. Firstly, we investigate the mutual interference and its influence on a WBSN's performance (see Chapter 2). A system model is then proposed for further simulation-based and test-bed experimental studies (see Chapter 3). Effective adaptive resource allocation schemes (adaptive frequency hopping and adaptive phase-shifting) are then proposed to mitigate the impact of mutual interference on a WBSN performance (see Chapter 4). For a given proposed scheme, the most influential system parameters on WBSN's performance are identified thereafter (see Chapter 5). The performance of all proposed schemes is then compared with each other (see Chapters 6 and 70), and finally, the possibility of embedding the best proposed scheme to the existing IEEE 802.15.4 standard protocol is then investigated (see Chapter 8).

1.5.1 Performance measures

In order to evaluate the performance of different proposed schemes and compare it with the performance of existing IEEE 802.15.4, a set of performance measures are used. The proposed performance measures are classified into *primary* and *secondary* performance measures for threshold-type applications. The primary performance measures are considered to capture the reliability of packet transmission, while the secondary performance measures focus on the energy consumption of the sensor nodes. These performance measure are explained as follows:

- **Satisfaction rate**: we regard an individual WBSN as *satisfied* when its average packet *success rate* (defined as the fraction of uplink packets generated by any sensor within the WBSN for which the originating sensor receives an acknowledgement from the coordinator) is 95 % or more. Thus, the satisfaction rate – as a primary performance measure – is defined as the percentage of satisfied WBSNs out of the given total number WBSNs.

- **Carrying capacity**: this (primary) performance measure is defined as the number of WBSNs which can, for a given scheme, be located on the same spot such that the large majority of them (at least 95% of the WBSNs) are satisfied.

- **Fraction of time without PAN coordinator**: When a sensor device becomes an orphan, it has to scan either the whole frequency spectrum (for frequency adaptive schemes) or the current channel (non-adaptive schemes) to find its associated coordinator. Therefore, the fraction of time that the sensor device is not associated to its corresponding coordinator is considered as the fraction of time without PAN coordinator which results in delays in transmission and packet losses. This performance measure is categorised in the secondary performance measure.

- **Energy consumption** This secondary performance measure focuses on the life time a WBSN. More specifically, the amount of energy consumed by both coordinator and sensor devices is measured individually and is presented as the sensor or coordinator energy consumption.

1.5.2 Hypotheses

Mutual interference and its destructive impact on a WBSN's performance has recently drawn much attention within the research community. In this thesis, we investigate the advantages of utilising the adaptive resource allocation approaches in the field of wireless (body) sensor networks. We have used simulation and real test-bed experiments to evaluate the following hypotheses:

- **Hypothesis 1:** As the number of WBSNs becomes larger and the mutual interference becomes more intense, an adaptive frequency hopping strategy (either randomly or using measurements) allows a WSBN to switch to the channel with the smallest number of occupants. Although utilising a frequency adaptation strategy could cause higher energy consumption (particularly for the coordinator node) and also would increase the risk of node orphaning, it is expected that the primary performance measures would be improved noticeably.

- **Hypothesis 2:** By preforming the sensitivity analysis of the satisfaction rate against the variation of a candidate set of system parameter configurations, it is expected to see that, for a range of system parameter variations, equal allocation of frequency spectrum (equal distribution of WBSNs over all available channels and equi-distantly spreading them over time) to all WBSNs will result in higher network performance compared to the frequency adaptation alone.

- **Hypothesis 3:** By introducing the adaptive phase-shifting strategy and coupling it with the adaptive frequency hopping strategy significant improvement of network performance could be achieved, compared to frequency adaptation alone.

- **Hypothesis 4:** The phase-shifting strategy can be designed in such a way that it can be fully compatible with the current commercialised sensor devices and no modifications or changes to the IEEE 802.15.4 standard MAC will be required.

1.5.3 Contributions

The following points are highlighted in this thesis:

- Firstly, a large number of IEEE 802.15.4-based WBSNs are uniformly distributed over 16 available channel to create scenarios where WBSNs experience mutual interference. This scheme is referred to as **static-random** scheme in which WBSNs closely follow the IEEE 802.15.4 standard. The term "static" is used because WBSNs are not allowed to leave the current operating frequency. This scheme is considered as the lower-bound of the achievable performance. Clearly, as the number of wireless body sensor networks becomes larger, the overlapping ratio of their active periods will be increased and eventually experiencing mutual interference will result in significant performance degradation.

- In order to minimise such overlapping ratio, a new scheme is designed called **static-idealized** in which WBSNs are evenly distributed over 16 available channels and also become equidistantly spread over time within each channel. This scheme – which which could be the output of a centralised resource allocation scheme – provides equal opportunity of channel access for each and every WBSN when they all operate concurrently. The static-idealized scheme is considered as a hypothetical upper band of what could be achieved. The gap observed by comparing the performance of the static-random scheme with the static-idealized scheme suggested that there are possibilities to shorten this gap.

- In order to provide an opportunity of being equally distributed over all available channels, a scheme called **static-initial-choice** scheme is proposed. In the static-initial-choice scheme, WBSNs are able to initially scan all 16 available channels and pick the channel with smallest number of occupants. Once the channel is determined, they should stay in that channel, throughout.

- In the nest attempt, we introduce the "dynamic" schemes in which a WBSN is able to adaptively switch to another operating frequency when its network performance has degraded below the threshold. The target operating frequency (to hop on) is either determined randomly (using uniform distribution which is called **dynamic-random-hopping** scheme) or using a measurement scheme (which is called **dynamic-targeted-hopping** scheme). According to the latter dynamic scheme, the coordinator of a WBSN either periodically or continuously assesses the network performance and, based on the mentioned network assessment behaviour, it performs the spectrum scanning procedure either periodically of continuously to track the channel with the smallest number of occupants. The performance of these dynamic schemes are compared with all previously-introduced static schemes.

- We analyse the sensitivity of satisfaction rate and packet success rate against the variation of some important system parameters. More specifically, the key goal of the sensitivity analysis carried out in this thesis is to explore how sensitive the satisfaction rate is to changes in a number of important system parameters, and to identify the factors having the strongest influence on the responses. Moreover, the result of this analysis would highlight the performance of the proposed schemes under the variation of system parameter configurations. To accomplish this we use the well-known Response Surface Methodology (RSM) and consider duty cycle parameters (beacon order and superframe order), CSMA/CA internal parameters (macMinBE and macMaxBE) and system load (packet inter-arrival time) as the candidate system parameters for this experiment.

- The dynamic-targeted-hopping scheme eventually achieves better distribution of WBSNs (most probably even distribution) over 16 available channels. In dynamic-targeted-hopping scheme WBSNs are able to adaptively switch to other operating frequencies, however, they all stick to their initial phase distributions and no phase-shifting occurs in this scheme except for clock-drifting.

- This has conveyed our research to the next attempt, where we propose a scheme called **adaptive phase-shifting** scheme in which WBSNs are able to share their views about the number of occupants in the present channel and shift their phases whenever it is required. In addition, a WBSN can switch to other operating frequency if the coordinator finds a channel with smallest number of occupants. In adaptive phase-shifting scheme, the phase-shifting procedure and the spectrum scanning procedure are performed in parallel with the minimum interaction.

- We also analyse the sensitivity of the satisfaction rate obtained by the adaptive phase-shifting scheme against the variation of previously-mentioned system parameter.

- To confirm the qualitative trends observed in simulation studies, an experimental study is carried out in which the dynamic-phase-shifting scheme is implemented on the real-world sensor devices. This experiment is conducted to evaluate the performance of phase-shifting algorithm in a setting without frequency adaptation.

1.6 Thesis Layout

Chapter 2 essentially describes the IEEE 802.15.4 standard MAC protocol and also provides necessary background information on the recently released 802.15.6 standard. The previous state of art associated with the impact of different system parameters as well as the mutual interference on the performance of WBSNs are also discussed in this chapter. The system model mainly including simulation scenarios, WBSN model and performance measures are introduced in Chapter 3. Thereafter, Chapter 4 elaborates the considered schemes followed by Chapter 5 in which how to analyse the sensitivity of WBSN's performance against the variation of some important system parameters is explained. The performance evaluation of both passive and active schemes are then discussed in Chapters 6 and 7, respectively. Chapter 8 provides an experimentation study including the test-bed setup and the evaluation of a scheme with the highest performance gain compared to the IEEE 802.15.4 standard MAC protocol. Finally, our research findings, evaluation of the hypotheses and future works are briefly discussed in Chapter 9.

2 Background and Literature Review

2.1 Background

This chapter explains the IEEE 802.15.4 device architecture in the form of layers. Moreover, the functionality of the MAC layer of this standard is described in this chapter. The internal interference and its impact on performance gain is also addressed in this chapter. Thereafter, the related state of art is discussed which comprises two main subsections, namely: 1) Internal Interference: Interaction of System Parameters; 2) Internal Interference: Interference Mitigation Approaches. Finally, the interference mitigation approaches offered in IEEE 802.15.6 (recently standardised protocol) are briefly discussed along with the reasons of choosing IEEE 802.15.4 over IEEE 802.15.6. This chapter is published in [79].

2.1.1 IEEE 802.15.4

The IEEE 802.15.4 standard [58, 124] is a well-established standard for low-power wireless sensor networks, which has also been considered as underlying technology for WBSNs, not the least due to the availability of cheap and mature components. Therefore, this thesis believes that the IEEE 802.15.4 will remain a serious contender in the field of WBSN for quite some time. The architecture of this standard is simply defined in terms of a number of layers. Each layer is responsible to accomplish the tasks related to the specific part of the standard. Furthermore, each layer offers certain services to the higher layers. A device that employs this standard comprises the Physical (PHY) and the MAC. The physical layer contains the Radio Frequency (RF) transceiver and the low-level control mechanism, While the MAC layer provides the access to the physical operating frequency (channel) for any transmission purposes. These layers are shown in Figure 2.1. Both network and application layers

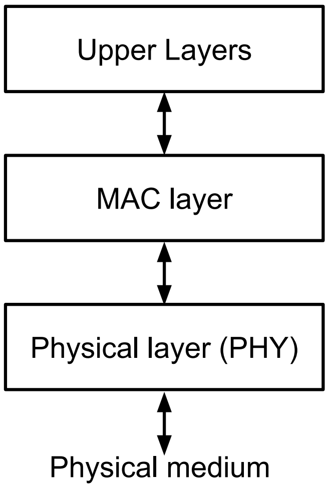


Figure 2.1: IEEE 802.15.4 device architecture

are considered in the upper layer block, shown in the Figure 2.1. Studying of these upper layers is outside the scope of this thesis.

Physical Layer

The physical layer of this standard offers 27 non-overlapping operating frequencies: In the IEEE 802.15.4 standard, different PHY layers are supported in 2.4 GHz band. Arguably, the most widespread and commonly-used band is the offset quadrature phase-shift keying PHY. In this paper, we are going to focus on this band simply due to the availability and the accessibility of the popular ChipCon CC2420 transceiver that is compliant to this band. The data rate in this band is 250 kb/s. The 2.4-GHz band is further subdivided into 16 non-overlapping channels. Each channel is 2 MHz wide, and the centres of two adjacent channels are separated by 5 MHz. In order to study the impact of internal interference, we only consider the interference caused by neighbouring WBSNs, and the interference caused by two adjacent channels is disregarded [110]. Additionally, the 2.4-GHz frequency band employs the Offset Quadrature Phase-shift Keying (O-QPSK) modulation along with interference mitigation mechanisms such as Direct Sequence Spread Spectrum (DSSS) and the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) to co-exist and share the same frequency spectrum with other technologies.

Medium Access Control Layer

Generally, the MAC layer manages and handles all access to the physical medium (operating frequency) and is mainly responsible for the followings:

- Creating the beacon packets (taking higher layer's requirements into consideration) if the device is a coordinator.
- Synchronisation
- Handling association and disassociation to the PAN coordinator
- Utilising the CSMA/CA mechanism for channel access
- Handling the GTS
- Establishing a reliable connection between two MAC entities.

There are two types of device namely: a Full Function Device (FFD) and a Reduced Function Device (RFD). The FFD is can serve as Personal Area Network (PAN) coordinator, a coordinator, or a device. However, an RFD only operates as a device that is responsible to fetch the information from the surrounding environment and transmit it to a single central entity (usually PAN coordinator). According to the IEEE 802.15.4 standard, there should be only one PAN coordinator per network. The main responsibilities of the PAN coordinator are defining the network parameters required for device synchronisation, coordinating, initiating, terminating, or route communication around the network. Two network topologies are offered in the IEEE 802.15.4 standard: 1) star topology; 2)Peer-to-Peer (P-to-P) topology. Employing either of them depends on the application requirements. Figure 2.2 depicts these network topologies.

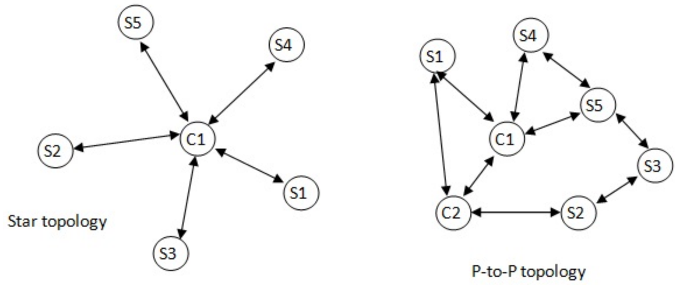


Figure 2.2: Star and peer-to-peer network topologies

In peer-to-peer (p-to-p) network topology, any device is able to communicate with any other device that is within its communication range. RFDs that are located outside of the communication range are able to communicate with each other through FFDs. Please note that RFDs are only able to connect to FFDs that are located within their communication range. Hence, more complex and flexible network formation can be implemented via using the p-to-p topology, e.g. mesh networks. Such network topology can be used in industrial and medical control monitoring, security, or animal tracking purposes.

Star network topology, however, is different in terms of the ability of RFDs to communicate with each other. This means that no direst packet is allowed between RFDs. If any packet is meant to be delivered from an RFD to another one, this has to be done through the coordinator node. In star topology an RFD is only able to connect to either a PAN coordinator or a coordinator node within its communication range. Although, this network topology seems to be less flexible, it is less complicated to control and manage this type to network due to the simple infrastructure. Therefore, star topology seems to be more suitable for WBSN applications. The star topology is utilised in this thesis to connect sensor devices to the coordinator node.

The IEEE 802.15.4 MAC layer offers two operation modes namely: **beacon-enabled** and **non-beacon-enabled** modes. In the beacon-enabled mode, **time** is split up into sequential time frames called **"Superframes"**. Superframes themselves are partitioned into an active and inactive periods. According to the IEEE 802.15.4 standard, all devices are able to turn to sleep mode (with the least energy consumption) during inactive period. This inactive period could be a suitable opportunity for coordinators to perform some beneficial measurement procedures that will be explained later on in this thesis.

A superframe starts with the transmission of a beacon packet by the coordinator without performing a carrier-sense operation. The beacon packet contains some information regarding to the network configuration and the pending downlink data packets. The length of the superframe and the relative length of active period within a superframe are configurable. The duration of a time between two consecutive beacon packets is called Beacon Interval (BI) and ranges from 15 ms to 245 s. The duration of active period is called super-frame Duration (SD). The lengths of both BI and SD are calculated by using Beacon Order (BO) and Superframe Order (SO), respectively:

$$BI = aBaseSuperframeDuration \times 2^{macBO}, 0 \leq macBO \leq 14 \tag{2.1}$$

$$SD = aBaseSuperframeDuration \times 2^{macSO}, 0 \leq macSO \leq macBO \leq 14 \tag{2.2}$$

where aBaseSuperframeDuration is the minimum duration of a superframe:

- BaseSuperframeDuration = aBaseSlotDuration * aNumSuperframeSlots
- aBaseSlotDuration = 60 symboles
- aNumSuperframeSlots = 16

Generally, the active portion of each superframe is divided to equally spaced slots of duration *aBaseSlotDuration* $\times 2^{macSO}$ and is comprised of three parts: a beacon, Contention Access Period (CAP) and Contention Free Period (CFP). The beacon is transmitted at the beginning of the active period (slot 0) without performing the CSMA/CA and the CAP starts immediately after the beacon is transmitted. The CFP, if present, starts immediately after the CAP and continues till the end of the active period. Figure 2.3 illustrates the superframe structure designed for IEEE 802.15.4 WSN/WBSN.

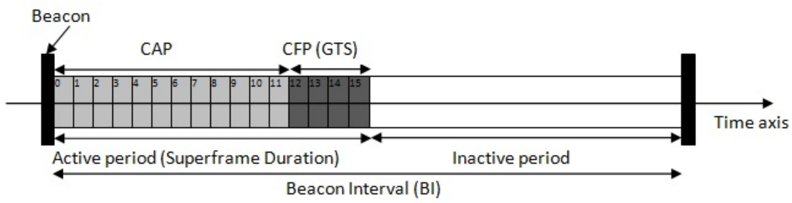


Figure 2.3: The Superframe structure

So in 2.4 GHz, rate may be 250 Kb/s or 62.5 K symb/s. Therefore for BO = 0, BI is 960 symbols or 15.36 ms. At the end of the active period (during CFP), a maximum of seven GTSs could be exclusively reserved for specific nodes where no carrier-sensing procedure is performed prior to transmission. During the CAP the associated nodes are able to transmit the data packets to the PAN coordinator and request the pending packets from the PAN coordinator. Moreover, during this period, nodes compete with each other to access to the medium using CSMA/CA or an ALOHA mechanisms. Previous studies shows that in the presence of interference, networks that used the CSMA/CA achieve higher performance gains (successful transmission of data packets) compared to the networks that used allocated GTS [121]. Therefore, in this thesis, it is assumed that networks is operated in beacon enabled mode and the CSMA/CA mechanism is employed by sensor devices to access the medium.

The coordinator as the body sensor network starter can initially scan all the available channels using passive or active MAC layer scan. The collected results can further be used by the higher layers to determine the operating frequency, duty cycle settings and PAN identifier. Thereafter, the coordinator periodically broadcasts the beacon packets. Once the beacon packets are transmitted, the sensors are able to discover their coordinators performing active or passive channel scan (refer to standard draft [58] subsection 5.1.2.1.2). To accomplish this, the sensors scan all channels and listen to each channel for a pre-determined duration to detect their coordinator's PAN identifier. It is assumed that the sensors know about the BO and they stay in each channel for the period of a BI before proceeding to scan the next channel. This assumption is considered to avoid the coordinator discovery procedure that is a time-consuming process [8, 106]. After discovering the coordinator, sensors attempt to associate with their coordinators via sending the association request packets during the CAP (refer to standard draft [58] subsection 5.1.3.1). Beacon packets are transmitted periodically to maintain the associated sensors synchronised with the coordinator (refer to standard draft [58] subsection 5.1.4.1). For example, a beacon packet generally may contain information such as announcing the pending download traffic for particular sensors, or allocation of GTS to some sensors. We assume that once a sensor discovered the first beacon packet, it maintains its synchronisation with that coordinator and attempts to receive the future beacon packets. As mentioned earlier, the beacon packet is transmitted periodically, and the period (depending on the value of the BO parameter) is determined using Equation (1). For instance, BO = 6 corresponds to BI = 0.98304 s, which means that the beacon packet is going to be transmitted every 0.98304 s. Generally, when a sensor does not receive four consecutive beacon packets, it concludes that the synchronisation with its associated coordinator has been lost and informs its higher layers, which then start the searching and association process again. The sensor that has lost its synchronisation is called an *orphan* sensor. An orphan sensor attempts to re-discover its correspondent coordinator, and meanwhile it cannot transmit or receive any data (refer to standard draft [58] sub- section 5.1.2.1.3). The data packets generated during the orphan time are buffered in the MAC layer and will be discarded and counted as lost packet once the buffer becomes full.

A possible way to find the currently associated coordinator is to scan the whole frequency spectrum. In the channel scanning procedure, the sensor is forced to stay in each channel for a beacon period and scans the channel for the entire time. Another possible way to find the corresponding coordinator the transmission of orphan notification command packet and waiting for the response [59, Sec. 5.3.6]. The latter method is used in non-beacon-enabled mode, since the coordinator is required to be awake at all times. After sending the orphan-notification command packet, if the sensor device received the realignment command packet (sent from the corresponding coordinator) within time (macResponseWaitTime), it would resume its routine activities as before. In this thesis we have employed the channel scanning procedure for coordinator discovery purposes. This is simply due to avoid a scenario where the coordinator is in inactive period and the orphan sensor device ineffectively attempts to re-associate with it via sending the orphan-notification command packet.

CSMA/CA Algorithm

If the WBSN is operating in "beacon-enabled" mode, the MAC (sublayer) employs the slotted[1] version of the CSMA/CA algorithm for transmissions during the CAP. Considering the slotted CSMA/CA, every sensor device in the WBSN is designated the backoff period boundaries [2]. These boundaries are aligned with the superframe slot boundaries of the PAN coordinator. For instance, the start point of backoff period for each sensor device could be aligned with the start of beacon packet transmission (which is what we considered in our study). Each sensor node maintains three variables for each transaction, namely: Number of Back-off (NB), Contention

[1] According to IEEE 802.15.4 standard draft, the unslotted CSMA/CA is deployed for non-beacon enabled mode or other circumstances such as when the beacon could not be located in the beacon-enabled WBSN.

[2] A basic time unit in CSMA/CA algorithm is called *backoff period* which is equal to *aUnitBackoffPeriod* = 80 bits (0.32 ms)

Window (CW) and Back-off Exponent (BE). NB is the number of times that the CSMA/CA algorithm is needed to back off while attempting the ongoing transaction. For each new transaction, this value is initialised to zero. CW is the contention window length, which represents the number of backoff periods that the channel needs to be clear (idle) before the commencement of the transaction. The value of this variable is initialised to *CW0* before each attempt of transmission and each time the channel is assessed to be busy, it is reset to *CW0*. BE is the backoff exponent, which represents how many backoff periods a sensor device should wait before attempting to assess the channel. Figure 2.4 shows the flowchart of the slotted CSMA/CA algorithm.

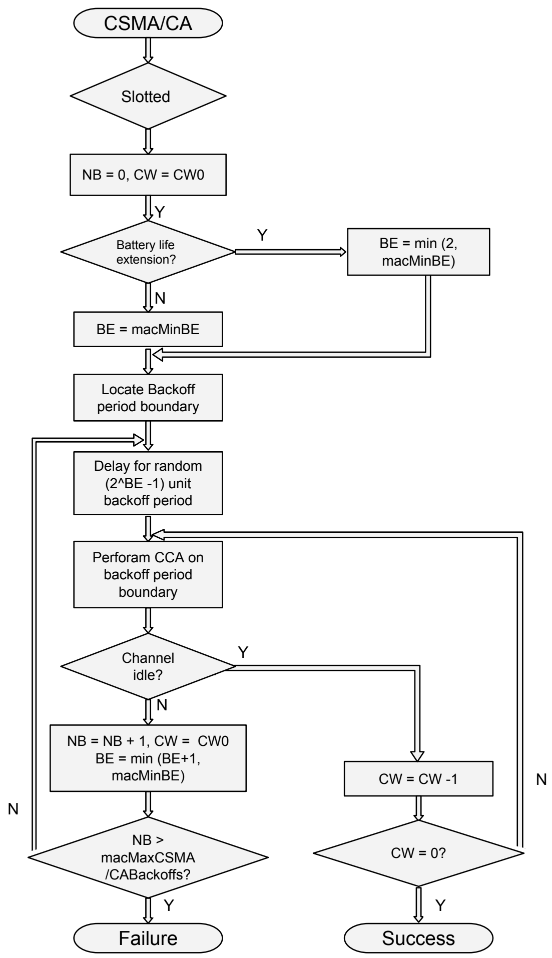


Figure 2.4: Slotted CSMA/CA flowchart

Once the packet reaches buffer, the backoff period boundary is located and the delay for a random number of units of backoff period is determined. The value of this random number is selected from the interval $[0,2^{BE}-1]$ using uniform distribution. *macMinBE* is the initial value of *BE*. Once the random delay is completed, the sensor device senses the channel on the backoff period boundary. If the channel is found free (idle), the value of CW is reduced by one unit and another carrier sensing is performed immediately, at that particular backoff period boundary. Only once the CW reaches 0 and the channel is still sensed idle, the packet could be transmitted. If the channel is found busy whenever before the CW reaches 0, NB will be incremented by one unit and a new random backoff will be started. As long as the value of NB does not exceed the maximum number of backoffs, this procedure continues. The Duration of this random backoff retry is determined from the interval $[0,2^{min(BE,macMaxBE)}-1]$ using uniform distribution. macMaxBE is the maximum value of backoff exponent. It must be noted that upon each random backoff retry the value of CW will be reset to its initial value.

2.1.2 Internal Interference

As previously mentioned, a superframe is divided into two periods: CAP and CFP. Generally, within a WBSN, communications between any two entities occur during the CAP. This infers that as the number of WBSNs becomes larger, the active periods of neighbouring WBSNs would highly likely to overlap on each other. Such overlapping will cause interference and would result in packet collisions and eventually performance degradation. In this thesis, the impact of interference caused by homogeneous WBSNs on the overall performance gain is investigated and thus the interference of other technologies such as WiFi or Bluetooth on WBSN performance is disregarded. The interference coming from co-located networks of the same technology and sharing the same frequency band is preferably called *internal* interference. Clearly, when active period of two or more WBSNs overlap on each other, the sensor devices of these WBSNs have to compete with each other to gain access to the channel. Since the sensor devices utilise the CSMA/CA mechanism to avoid packet collisions, the internal parameters of the CSMA/CA mechanism seem to play important role in the performance of CSMA/CA and eventually the overall performance gain of WBSN.

2.2 Internal Interference: Interference Mitigation Approaches

Channel coexistence is considered as one of the most important challenges in IEEE 802.15.4. Several investigations have been conducted to study and evaluate the performance of the wireless systems when the spectrum is utilised either homogeneously or heterogeneously. In this part, we highlight the latest approaches that have addressed the challenges regarding with homogeneous coexistence of IEEE 802.15.4-based WSNs.

One of the key ideas to resolve the issues caused by channel coexistence (e.g. internal interference) is to make the system more flexible with dynamic operating frequency allocation. The main goal is to minimise the packet collision caused by multiple IEEE 802.15.4-based systems that are using the same operating frequency at the same time. The first step towards tackling the interference caused by neighbouring WSNs is to employ an interference detection technique: ED, which is done through CCA attempt offered in IEEE 802.15.4 and uses the RSSI service (in PHY layer) [47, 71]. The RSSI measurement may suit well to detect the interference caused by WiFi technology as the traffic load continuously exist and different carrier sensing strategy is deployed. However, deployment of such measurement does not provide reliable information about possible interference in homogeneous WSNs with periodic transmission. Packet Error Rate (PER) and LQI measurements are also considered as the other two popular and commonly used interference detection techniques [123]. Many researches have been conducted to determine the efficiency of the above-mentioned interference detection techniques. For in-depth information about the efficiency of such techniques please see [102, 108]. Several schemes and approaches have been proposed by researchers to alleviate the destructive effects of external interference (mostly caused by WiFi technology) on the performance gains of WSNs/WBSN [122], [123] and [109]. However, In this survey we only focus on the impacts of Internal interference caused by neighbouring homogeneous WSNs on their performance gains.

The IEEE Standard for Local and metropolitan area networks [1], has recently standardised Wireless Body Area Network (WBAN) to address the critical requirement of health related application in the field of wireless body sensor networks. IEEE 802.15.6 MAC protocol has introduced four strategies to mitigate the interference caused by neighbouring WBANs: (1) beacon-shifting, where the shifting offset is included in the beacon packet. The coordinator must select the proper shifting offset to avoid further beacon collisions. (2) Channel hopping could be only enabled in narrow band with PHY not operating in the Medical Implant Communication Service (MICS) or a frequency modulation of ultra-wide band. In the aforementioned cases, upon including the certain information in the beacons, the coordinator may change its operating frequency periodically. (3) Active superframe interleaving, where a BAN is able to negotiate with other BANs to share the same operating frequency through sending command-active-superframe-interleaving-request frame in the beacon-enabled mode WBANs. (4) B2-aided time-shifting, where the functionality is similar to active superframe interleaving and is only applicable for non-beacon-enabled mode.

Although the IEEE 802.15.6 MAC protocol is specifically designed to address body sensor networks, we have not simulated this technology simply because of being currently commercially unavailable that makes this standard arguably immature. The aforementioned strategies could solve the problem of channel coexistence but only to some extent. For example, when the number of active WBANs is relatively small, utilising the beacon-shifting approach assists WBANs to adjust their beacons to avoid active period overlapping.

A flexible beacon scheduling scheme is proposed in [50] where coordinators have to perform the carrier sensing before the beacon transmission. Their proposed approach is then compared with the beacon-shifting approach offered in IEEE 802.15.6 MAC protocol. The results indicate significance improvements in terms of successful transmission over the beacon-shifting strategy. It must be noted that in IEEE 802.15.4 beacon transmission occurs regardless of the status of the channel (busy or not). Besides, as the number of occupants of the channel increases the probability of flexible beacon scheduling failure will increase as well, due to sensing the busy channel and being compelled to back off. Another simulation study was conducted to compare the performance of IEEE 802.15.4 with IEEE 802.15.6 [17]. The simulation study indicates that IEEE 802.15.4 outperforms the IEEE 802.15.6 in terms of throughput.

In our previous studies, we have evaluated the performance of IEEE 802.15.4 MAC protocol to find the potential white spaces [82], [83]. The channel utilisation is classified into three – white, grey and red – regions, which represent if a given channel is idle, being used by one user or overlapped with two or more neighbouring WSNs, respectively. Figure 2.5 represents the channel utilisation classifications.

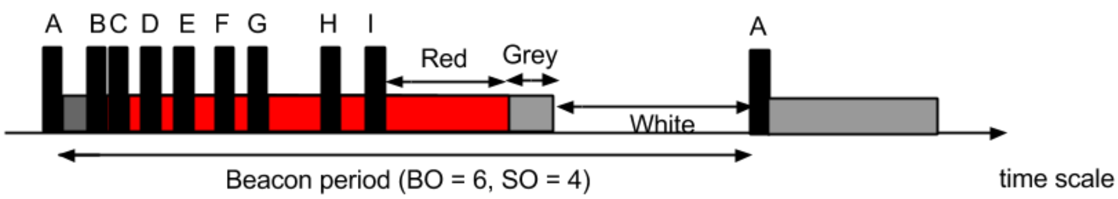


Figure 2.5: The channel utilization characteristics

We have studied the percentage of channel utilisation as the network density increases. Preliminary schemes are proposed (blind, idealised, initial choice and greedy) to detect the existence of overlapping neighbouring networks without the need for a centralised coordination infrastructure. The greedy scheme enabled the

WSNs to adapt their schedule in order to minimise the red region. Nevertheless, the greedy has its drawbacks. As the number of networks per channel increases, the amount of gaps would decrease. Therefore, the arrival of additional networks would result in their starvation in terms of channel access. Later scheme introduced frequency adaptation feature [76]. Frequency adaptation feature enables WSN/WBSN to switch to a channel with the lowest interference. Whereas the aforementioned greedy scheme assists WSNs to utilise the currently occupied operating frequency, more efficiently. In frequency adaptive schemes, the coordinator actively takes samples from each channel during the inactive periods. This samples reveals the information of the occupancy load of each and every available channels. Although this would increase the energy consumption of the coordinator, the attained information is definitely useful when a WBSN decides to switch to the other channel. The coordinator assesses the quality of the current channel in order to decide whether to stay on the current channel or to hop to another one. Therefore, two channel- quality assessment strategies were offered to the coordinators: periodic assessment and continuous assessment. According to the periodic-assessment strategy, the coordinator waits for a specific period of time and then assesses the channel quality. Whereas, according to continuous-assessment strategy, the coordinator actively assesses the channel quality. This enables the coordinator to switch to the other channel at the exact time that the channel-quality has degraded below the threshold [77]. A new study has shown that phase-shifting strategy can be effectively useful to improve the performance gain of WBSNs [78].

Cognitive Radio (CR) networks provide the opportunity of sharing the same frequency spectrum with Primary User (PU) of that particular frequency spectrum in an opportunistic manner. CR users are equipped with the dynamic spectrum access capability that allows them to identify the portion of the spectrum that is available for potential transmissions. This technology is designed to address the channel scarcity in the 2.4-GHz ISM band where the frequency spectrum is inefficiently utilised. It must be noted that in CR technology, the primary users' transmission must be left unharmed. This implies exchanging essential information in order to assure the spectrum availability between the given pair of nodes before commencing the data transmission. Because this information exchange is considered to be the MAC protocol responsibility, several researches have highlighted the problem of MAC protocol for CR networks and proposed effective solutions to maximise the coexistence of both homogeneous and heterogeneous technologies in the same frequency spectrum [11], [12]. Although their proposed solutions may suit well with the requirement of the CR users, they are not suitable for unlicensed 2.4 GHz frequency spectrum where a large number of homogeneous wireless technologies (i.e. WBSN) attempt to utilise the same frequency spectrum without any priority consideration in advance.

Deylami *et al.* have studied the effects of the coexistence of the performance of IEEE 802.15.4, and proposed a distributed mechanism called the Dynamic Coexistence Management (DCM) to reduce the negative impacts of dynamic coexistence [35][36] [34]. According to the functionality of the DCM mechanism, the coordinator concludes that there is a coexistence if it does not receive any data packets from the associated sensor nodes. Thereafter, the coordinator monitors the current operating channel for a duration of a BI to see if there is a gap or not. If a desired gap is found, the coordinator will re-schedule the transmission of the next beacon at the beginning of the gap. Otherwise, the beacon will be replaced at the beginning of the largest gap. Channel switching is also offered in DCM where the coordinator switches to the next channel to find the potential gap through scanning the channel for the period of a "full" BI or "inactive period" of a superframe. It must be noted that if the coordinator was not successful in finding any proper gap, the channel switching procedure will be repeatedly performed for other channels until a desired gap is found. The scanning method proposed in DCM mechanism could cause sensor nodes to loose their synchronisation with the coordinator more frequently. Moreover, deployment of DCM mechanism compels sensor nodes to keep their transceivers on for longer period of time. This results in higher energy consumption where sensors are energy constraint. Figure 2.6 represents the searching process for the candidate channel and replacing the superframe in the DCM.

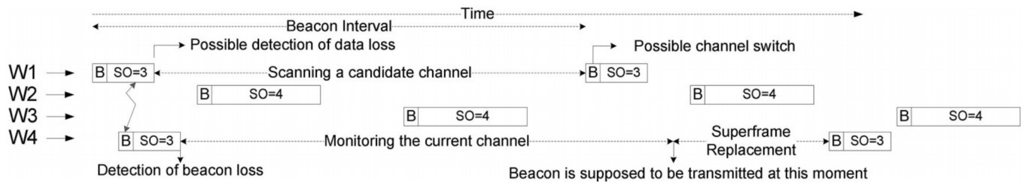


Figure 2.6: The searching process for the candidate and replacing the superframe in the DCM

Using multi-Channel MAC (CMAC) strategy is another approach for reliable data packet transmission in the presence of internal interference. Utilising the Request To Send (RTS) and Clear To Send (CTS) in CAP and modifying them (adding extra sub-field) have resulted in smaller average end-to-end delay [117]. However, it is highly likely that adding these two packets in the CAP would cause collisions as the number of active WBSNs increases. Besides, it is not clearly mentioned that how a sensor device has provided the information regarding other channels status (either free or busy). A survey of using multi-channel strategy is provided in [44]. The main goal of deployment of multi-channel approach is to offer more reliable data packet transmission [52]. Light traffic and small number of active WSN/WBSN are the main assumption for these proposed approaches.

Single fixed channel approaches are commonly used in WSN applications, mainly due to their simplicity and lower power consumption [33]. However, nowadays many low-power sensor network nodes are equipped with radio transceivers capable of operating on multi-channels and/or multi-bands [118], [37], [6], [68] and [120]. One of the objectives of multi-channel MAC protocols is to increase the throughput of network in the presence of interference. The drawback of such protocols is that under light channel interference they are less energy-efficient in comparison to single-channel protocols. An energy efficient multi-channel MAC protocol for WSN, called

Y-MAC is proposed in [53]. Y-MAC is capable of achieving high performance while being energy efficient for both moderate and high traffic conditions when the performance of sensor networks are threatened by internal interference. Using multiple transceivers on a WSN device increases the total performance gains and reduces the energy consumption. However, they could be achieved at the price of higher costs and complexity. Whereas lower costs and complexity along with smaller size of the sensor devices are the important factors that should be given a serious attention when dealing with WBSNs.

The concept of "Virtual Channel" is introduced in [51]. Virtual channel strategy is meant to provide the opportunity of increasing the number of available channels through efficiently managing the given spectral and temporal resources. In this approach, the throughout estimation of the IEEE 802.15.4 CSMA/CA is fed to a superframe scheduler. Thereafter, the selecting of the logical channel accompanied with the superframe scheduling approach would result in creation of a virtual channel. This approach requires a "management entity" to provide such information for up coming WSNs. The main shortcoming of the central management approaches is when the manager entity becomes out of order, the whole system encounters a great deal of agitation. Dynamic Channel Allocation (DCA) is proposed in [29] to minimise the interference caused by neighbouring sensor nodes. The DCA is based on what is proposed in graph colouring. In this approach, the colour repetition occurs only if the nodes are separated by more than two hops. The DCA tends to assign optimally the minimum channels in a distributed manner. Once the channel is assigned, the desynchronised multi-channel MAC takes over the responsibility of the conventional MAC protocol. The multi-channel MAC allows the maximum possible sleep time, prevents overhearing and offers the minimal control overhead. However, the maximum number of sensor nodes under investigation is 10 sensor devices which is relatively a small number to study the internal interference.

Table 2.1 presents some of the latest proposed approaches and offered strategies to mitigate the destructive impact of internal interference in homogeneous WSNs.

Several surveys can be found that address the challenges and probable solutions in the area of WSNs/WBSNs/WBANs [25, 26, 85]. Some of them provide readers with the general overview of application, functional and technical requirements of the BAN [22, 90]. Some other surveys present the overview of the characteristics and limitations of the sensor nodes that are commonly deployed in the WBSNs [40]. Many surveys have focused on the application point of view with the special emphasis on medical and health-related aspects. They have also revealed the issues encountered by healthcare systems [14, 88, 111]. For instance, patient-mobility could be considered as a potential issue in the hospital while wearing a WBSN. Therefore, Caldeira *et al.* [20] have surveyed the handover strategy for intra-mobility where the sensors are able to move around within the same network domain but different access points. Carrano *et al.* [24] have focused on the energy consumption of the sensor nodes through managing the duty cycle, while Sudevalayam *et al.* [105] have considered the applicability of the energy harvesting techniques on WBANs using the human body as the source of energy. Khanafer *et al.* [49] have focused on some strategies to mitigate the impact of interference on performance gains. However, in contrast to the above-mentioned surveys, this thesis specifically deals with the internal interference caused by neighbouring WBSNs. More particularly, the impact of system parameters on WBSN's performance gain is investigated from two perspectives: MAC parameters and protocol design. Furthermore, an extensive simulation study has been conducted to clarify the impacts of MAC parameters on WBSN's performance gain in the presence of intensifying internal interference.

Table 2.1: The analogy of State of art in terms of proposed approaches and strategies

	Problem Statement	**Proposed solution**	**Evaluation Methods and Verification Tools**
[1]	channel coexistence	beacon-shifting, channel-hopping and active superframe interleaving	Not specified
[50]	channel coexistence	flexible beacon scheduling scheme for IEEE 802.15.6	Castalia 3.2 simulator
[17]	channel coexistence	comparison between IEEE 802.15.6 and IEEE 802.15.6	Castalia 3.2 simulator
[82]	internal interference in homogeneous WBSNs and channel scarcity	initial-choice and idealised schemes (introduced as upper band)	Castalia 3.2 simulator
[83]	internal interference in homogeneous WBSNs and channel scarcity	greedy channel utilisation approach	Castalia 3.2 simulator
[76]	internal interference in homogeneous WBSNs and channel scarcity	continuous-hopping approach	Castalia 3.2 simulator
[77]	internal interference in homogeneous WBSNs and channel scarcity	continuous-assessment vs periodic-assessment	Castalia 3.2 simulator
[11]	channel assignment problem	segment-based channel assignment strategy	analytical and simulation
[12]	low performance gains due to channel coexistence	coexistence-aware spectrum sharing protocol	analytical and simulation
[36]	low performance gains due to channel coexistence	coexistence detection and coexistence mitigation strategies	OPNET simulator
[35]	low performance gains due to channel coexistence	dynamic coexistence management (DCM) mechanism	OPNET simulator
[34]	low performance gains due to channel coexistence	dynamic coexistence management (DCM) mechanism	test-bed experiment (Markov model)
[117]	low reliability and high delay due to internal interference	multi-channel MAC protocol approach	—
[44]	destructive impacts of internal interference on sensor network performance gains	advantages and disadvantages of various proposed multi-channel communication approaches	analytical modelling (Markov model)
[52]	increasing the nodes density and escalation of internal interference	an energy efficient multi-channel MAC protocol approach	test-bed experiments
[118]	coexistence with other technologies	multi-radio prototype	test-bed experiment
[37]	coexistence with other technologies	dynamic spectrum access strategy	test-bed experiment (Iris platform)
[6]	performance degradation due to spectrum congestion caused by increasing the popularity of wireless embedded devices	a low-power spectrum agile MAC protocol	analytical analysis and test-bed experiment (TelosB platform)
[68]	the current multi-channel MAC protocols are being inflexible to the variation of the environment	Dynamic Multi-radio Multi-channel MAC (DMMAC)	test-bed experiment
[120]	performance degradation due to radio interference	coordinated channel switching and spectral multiplexing	test-bed experiment (Mica2 sensor nodes)
[51]	channel scarcity	Scheduler Using Throughput Estimator (SUTE), Nearest Vacancy Search (NEVS)	ns_2
[29]	internal interference	dynamic channel assignment (DCA) and CMAC	JAVA based discrete event (SimJava)

2.3 Internal Interference: IEEE 802.15.6 Interference Mitigation Approaches

In February 2012, the IEEE Standards Association introduced the IEEE 802.15.6 standard for WBANs [2]. This standard was designed to provide reliable wireless communication for extremely low-power devices used in close proximity to or inside the human body. It supports the following three physical layers: NB[3], Ultra-Wide-Band (UWB)[4], and the Human Body Communications (HBC)[5] physical layer. According to the IEEE 802.15.6 standard, a WBSN is capable of operating on at least one of 241 available frequency channels. Amongst these, 230 channels are available in the narrow band, 10 frequency channels are available in the UWB, and one channel is available in the HBC range. This standard also supports a wide range of data rates, starting from 75.9 Kbps up to 10 Mbps.

The MAC layer specification permits a network to form a star topology with only one hub. The number of nodes ranges from zero to mMaxBANSize. With the aid of relay-capable nodes, end devices are able to be placed either one hop or two hops away from their corresponding hub. In this standard, time is divided into super-frames. A super-frame structure is bounded by beacons. The beacon period and time slot allocation are selected by the hub. The hub is also able to shift the offsets of the beacon periods. These networks are able to operate in one of the following three access modes [2, Sec. 6.3]: 1) Beacon mode with beacon periods (super-frames), 2) Non-beacon mode with super-frames, and 3) Non-beacon mode without super-frames.

Although this standard is specifically aimed and designed for WBANs [56], this thesis decides not to use this technology simply because this standard has just recently been introduced and – to the best knowledge of the author – no commercially available hardware exists (at the time when this thesis was submitted) that is compatible with the specifications of this standard.

[3]A compliant device with a narrow band-compatible physical layers shall be able to operate in one or more of the following frequency bands: 402-405 MHz, 420-450 MHz, 863-870 MHz, 902-928 MHz, 950-958 MHz, 2360-2400 MHz, and 2400-2483.5 MHz.

[4]The 10 frequency channels are divided into two groups: 1)Low band (3494.4, 3993.6, and 4492.8 MHz) 2) High band (6498.6, 6488.8, 7488.0, 7987.2, 8486.4, 8985.6, 9484.8 and 9984.0 MHz).

[5]A HBC-compatible transceiver operates in the 21 MHz frequency band.

2.4 Internal Interference: Interaction of System Parameters

According to the beacon-enabled mode of IEEE 802.15.4, sensor nodes compete with each other to gain access to the medium. Sensor nodes use a TDMA strategy to compete with other nodes. CSMA/CA is the most commonly used strategy in IEEE 802.5.4 (see section 5.1.1.4 in [58]). This enables sensor nodes to make sure the channel is not currently utilised by other sensor nodes. CSMA/CA strategy has its own internal parameters such as BE, macMinBE and macMaxBE. The following literature explains the importance of CSMA/CA internal parameters (mainly macMinBE and macMaxBE). Many investigations are conducted to study the impact of CSMA/CA internal parameters on WSN/WBSN performance. Koubaa *et al.* [54] presented the performance of CSMA/CA algorithm of IEEE 802.15.4 while the beacon-enabled mode is deployed. In their study the performance of slotted CSMA/CA is scrutinised for the configuration of different network parameters. More particularly, the impact of BO, SO and BE on the network performance (throughput, average delay and probability of success) were studied. The results show significant increase on network throughput as the offered load (G) varied from 50% to 300%. This is mainly due to two reasons: firstly, the overhead of beacon packet is more noticeable for the lower SO values because the beacon packets are more frequently transmitted; secondly, the frequent Clear Channel Assessment (CCA) in lower SO values could cause more collisions at the start of each superframe. For higher offered loads, the network throughput reached the relative saturation level that in their case, is approximately 62%. The success probability, however, drastically dropped as the offered load has increased. The offered G of lower than 50% owns the highest probability of success rate when the SO$\geq$1. The difference between their conducted research and our simulation study is the lack of consideration of varying WBSN density, and the impact of interference on network performance gains. Furthermore, the values of CSMA/CA parameters (i.e. macMinBE and macMaxBE) were constant throughout their simulation study, whereas in our simulation study, various values for macMinBE and macMaxBE are considered. Please note that the attained results presented in [54] did not match with the mathematical model proposed by the authors. Therefore, Park *et al.* [89] proposed an improved Markov model to fully represent the behaviour of the CSMA/CA strategy being followed in IEEE 802.15.4 standard. Their proposed Markov model is further verified by using the simulation analysis Network Simulator version 2 (NS-2). The main advantage of the Park's study compared the one proposed in [54] is that it considers the probability of the channel sensing state instead of channel accessing state. The channel accessing state is not suitable for describing the behaviour of the CSMA/CA strategy. This is mainly because in the improved strategy, channel sensing occurs twice before entering to the channel accessing state. Park *et al.* [89] showed that measuring the channel sensing state instead of the channel accessing state results in better matching of the mathematical analysis with the simulation results. However, the improved version of the model did not seem to appropriately following the CSMA/CA behaviour proposed for IEEE 802.15.4.

Some other researchers had performed the analytical evaluation of the CSMA/CA performance operated in IEEE 802.15.4 MAC layer [13] and [30]. They have proposed a Markov model that predicts the behaviour of the slotted slotted CSMA/CA mechanism being performed by IEEE 802.15.4 standard. However, the simulation results failed to match with their proposed Markov model. Therefore, a detailed analytical evaluation of the CSMA/CA performance in IEEE 802.15.4 is proposed in [96]. Pollin *et al.* [96] present a Markov model that predicts the behaviour of the slotted CSMA/CA mechanism being performed by IEEE 802.15.4 standard. The obtained results were further compared with the simulation results (the Monte-Carlo simulation procedure) to verify their accuracy. Their analysis was inspired by [13] and [30] but only for the usage of a per user Markov model. In [96], the state of each user at a particular moment was retrieved. Pollin *et al.* [96] proposed a Markov model that not only fully reflects the behaviour of the CSMA/CA mechanism for IEEE 802.15.4 but also verifies by looking at the simulation results. They have conducted an analytical study They have conducted an analytical study on the performance of CSMA/CA in both saturation and unsaturation networks. It is concluded that the larger macMinBE values are more suitable for saturated network, whereas smaller values of macMinBE could slightly improve the energy consumption in unsaturated networks. The probability of sending packets in different scenarios is varied accordingly. It is shown that the probability of sending packets is higher in saturated traffic when no acknowledgement packet is deployed. However, due to higher collision probability, the network throughput is very low. Although smaller number of packets are sent in periodic scenarios with unsaturated traffic, more throughput is achieved because of lower collision probability. In the aforementioned studies, the impact of internal interference on the performance of sensor network was not considered, which is the key difference compared with our study.

Previous mathematical models (Markov chain models), were offered in a memoryless fashion. This has caused the analytical models to be unable to fully represent the characteristics of the unsaturated WSNs (where sensor nodes do not always have data packets to transmit). Therefore, Ling *et al.* [66] proposed another analytical model called “a renewal analytic model” that addressed the observed limitations in previous mathematical models. In their proposed analytical model, it is assumed that the probability of starting to sense the channel (in a randomly selected slot) is fixed for each node and all sensor nodes attempt to re-transmit their data packets until they succeed. The results show a dramatic decrease in throughput, while the average service time âĂŞ the fraction of time between the moment that the data packet is located at the head-of-line and the time instance that it is removed because of either successful transmission, exceeding the maximum re-transmissions, or exceeding the maximum number of consecutive CCA failures âĂŞ represents the opposite trend as the number of sensor nodes increases. This is mainly due to small value of macMinBE = 3 and the macMaxBE = 5. Please note that according to IEEE 802.15.4 standard draft, both values are the default values for the macMinBE and the macMaxBE. Moreover, the backoff slots are uniformly distributed over a relatively short range of [0,31] which results in the execution of concurrent chan- nel sensing by multiple sensor nodes as the network size increases. This would finally result in higher throughput degradation.

Lee *et al.* [63] improved the previously introduced renewal model and made it applicable for unsaturated IEEE 802.15.4-based networks including acknowledgement packets. Frame dropping (due to transmission failure) is also considered in their proposed analytical model. The collected results indicate that, as the packet-arrival ratio increases, the probability of data packet dropping increases as well, which consequently results in dramatic decrease in successful transmission. Another interesting achievement of their study is that increasing the number of sensor node could result in experiencing larger average service time, while the throughput follows the opposite trend. When the network size is small (e.g.N = 5), the throughput drops as both values of macMinBE and macMaxBE become larger. The throughput, however, follows an upward trend as the network size becomes larger (e.g. N = 10). This is because when a sensor node attempts to transmit a data packet, in the small network size scenario, it spends unnecessary amount of time for backoff purposes (large number of macMinBE and macMAxBE), whereas in the larger network size, spending larger amount of time becomes necessary to avoid collisions. Therefore, as the number of sensor nodes increases, it is expected to encounter higher throughput as well Although Lee *et al.* [63] have considered the impact of internal interference on the performance of CSMA/CA indirectly, the interaction between CSMA/CA internal parameters and other IEEE 802.15.4 system parameters has not been taken into consideration. This has made our study to be fairly different with the research conducted by them.

A Markov chain analytical model that covers both slotted and unslotted CSMA/CA mechanisms is proposed in [115]. In the proposed model, both node model and channel model are integrated into one model. Considering the achieved results, the throughput increases as the number of states became larger while keeping the data transmission constant in value (314 bit). This means that for the constant data transmission, the collision probability decreases as the number of states increases. Interestingly, as the number of states increases, it becomes highly likely to detect the busy channel in the first CCA attempt. However, according to second CCA attempt, the probability of sensing the busy channel shows the downward trend. Please note that the value of data packet transmission was fixed during the first and the second CCA attempts. OPNET network simulator was used to validate the accuracy of the results obtained from the analytical model. In their considered scenario, the values of system parameters were fixed throughout.

Linear Increase Back-off (LIB) is the modified slotted CSMA/CA mechanism proposed by Zhu *et al.* [125]. LIB is designed based on an accurate Markov chain model. The main goal of LIB is to evaluate the performance of unsaturated, unacknowledged, one-hop star topology IEEE 802.15.4 MAC protocol operating in beacon-enabled mode. More specifically, the LIB targets to identify the possible con- gestions and improve the latency and delay while maintaining the energy efficiency and throughput at the reasonable levels. According to their analytical and simulation results, the probability of sens- ing the channel as the busy channel in the first CCA attempt increases significantly as the number of nodes and the unit backoff period become larger. However, the probability of sensing the busy channel in the second CCA attempt is less sensitive to the unit backoff period but increases with the number of nodes. The simulation results for throughput indicate that the value of the first backoff counter plays a key role to determine the throughput. The small backoff counter causes the sensor nodes to start sensing the channel simultaneously that eventually results in higher collisions. On the other hand, configuring a too large value for the backoff period would also result in lower through- put due to aggregation of the large number of packets at the slot boundary. This implies that sensor nodes are required to wait for longer backoff period before sensing the channel. The study fully presented the dependability of the throughput on the number of active nodes and the unit backoff period. However, their interactions with other system parameters are not considered.

Many analytical models for CSMA/CA mechanism in IEEE 802.15.4 MAC protocol have been proposed to reduce the energy consumption of sensor nodes by improving the CSMA/CA mechanism. An energy-conserving model is proposed to enhance the energy consumption while performing the CSMA/CA mechanism under a set of particular assumptions [103] and [104]. A stochastic model for CSMA/CA, where the performance is evaluated based on the collision windows, is proposed in [21]. It is shown that the energy consumption of the sensor nodes is investigated when the CSMA/CA algorithm is performed. According to the obtained results, the sensor lifetime can be drastically decreased for the CCA higher than the 30%.

Many investigations are conducted to determine the effectiveness of the role of traffic loads on the CSMA/CA and eventually the sensor network performance. Baz *et al.* [9] have proposed two algorithms to improve the CSMA/CA functionality. Their proposed CSMA/CA mechanism contains two strategies namely: *time-based frame aggregation* strategy and *selective frame* strategy. Each strategy is deployed based on the network density and the size of data packets. They have also proposed a versatile approach to model the CSMA/CA protocol for IEEE 802.15.4 standard based on the theory of compound probability distributions [10]. According to the latter study, it is revealed that the lowest service time and the least energy consumption accompanied with non-stable throughput are the main characteristics of the unacknowledged mode. Additionally, “limited” and “unlimited” number of data packet re-transmissions could result in the improvement and reduction of the stability of throughput, respectively. A priority-based/service differentiated, adaptive algorithm is proposed in [119] to increase the Quality of Service (QoS) for slotted CSMA/CA mechanism where the backoff exponents are initialised dynamically according to traffic variations. Their simulation results indicate the significant improvement of success rate, effective data rate and average delay. A major defect of standardised CSMA/CA algorithm is shown in [67]. It is shown that assigning the length of backoff period without considering the current channel condition could degrade the overall performance gains. Moreover, adaptive backoff determination and priority-based service differentiation are the two contributions mentioned in their research.

The aforementioned state of art discussed about the criticality of the CSMA/CA internal parameters (more specifically macMinBE and macMaxBE) and their impacts on the overall performance gains. We now focus on other system parameters and their impacts on the WSN/WBSN performance gains. Several studies have been conducted to determine the impact of various system parameters on the overall WSN/WBSN performance gains. Golmie *et al.* [39] have studied the performance of IEEE 802.15.4 n the presence of internal and external interference. According to the obtained results, although the end-to-end delay of high data load (1500 bytes) decreased significantly, the "goodput" dropped dramatically as the number of transmitters became larger. This was mainly due to the partitioning of the big data packets into the smaller size and waiting for the opportunity to transmit them to the receiver during the current and upcoming CAPs. This decreases the average end-to-end delay. Please note that in their configuration, if the transmission of a single partition failed, the remaining partitions would be deleted from the queue. This would result in a lower success rate compared with other traffic loads. In the second phase of their study, two WPANs (each consists of four medical applications) are considered for each patient. Both WPANs are configured to utilise the same operating frequency. The results indicate the significant packet losses for high traffic loads as the number of transmitters was increased.

The configuration and the optimisation of the network setup are discussed in [91]. In the simulated scenario, a patient uses an ElectroCardioGram (EGG) and blood analysis module to study the protocol parameters for the network behaviour optimisation as well as lowering the energy consumption. In that study, the impact of varying values of the BI parameter on energy consumption, packet loss ratio, medium access delay and packet transmission retries is investigated. According to the simulation results (where BO = SO), the BO values lower than 3 consume more energy compared with higher values. This is mainly due to relatively high network traffic load (56 192 bps) and short superframe duration that eventually results in deferring data packets to the next BI. This could increase the probability of packet collision at the first time slot of the next BI. Therefore, packets will be lost, and higher packet re-transmission ratio will be expected. Thus, higher energy consumption is inevitable. The same reasoning is applied for the packet loss ratio. Although, they have configured the commonly-used values for some network parameters (as in [39]), the impacts of interference caused by multiple neighbouring WBSNs as well as various values for data packet generation and CSMA/CA internal parameters have not been taken into consideration.

In [73], the impact of various system parameters such as packet arrival rate, number of sensors, buffer size, packet size and inactive periods on the performance of sensor networks is investigated. The results indicate that the average access delay (even for small buffer size) becomes very large if the throughput exceeds 50%. In order to achieve even higher throughput, the larger buffer size is required. They have also investigated the impacts of packet arrival rate, buffer size, packet size and the inactive period on the IEEE 802.15.4 network performance gains with another set of performance measures, [74] namely, the probability of access probability that the medium is idle, and the blocking probability was considered as the main performance measures. According to the obtained results, either the network size or packet arrival rate must be carefully determined in order to avoid higher blocking probability (the probability that a packet will be blocked due to insufficient capacity of the device buffer during the backoff period). Furthermore, the study indicates that the larger buffer size would provide the opportunity of increasing both packet arrival rate and number of stations.

The challenges and issues caused by various system parameters, for example, packet arrival patterns (Poisson or periodic), different values of CSMA/CA parameters, BI, various packet size and different offered loads are investigated in [5]. The results indicate that when data packets are generated periodically, all nodes compete to access the channel at the beginning of the active period, which results in less delivery ratio. On the contrary, in scenarios where Poisson data arrival pattern is utilised, not all nodes have to contend for channel access at the beginning of the CAP. However, the contention is more likely to happen even when the CAP length is relatively small compare with BI length. This infers that the IEEE 802.15.4 MAC layer has difficulties to handle the contention efficiently. Although a wide range of system parameters and their impacts on WSN performance gains are considered in their study, their research lacks the impact of the aforementioned effective system parameters in the presence of intensifying internal interference that is the key difference compared with our simulation study.

Clearly, data packet delivery ratio is directly related to the size of the CAP (SO) and the length of the BI (BO). As mentioned earlier, the contention is more likely to happen when the CAP is relatively small compared with the BI length. Long BIs might also cause the buffer overflow and eventually discarding the data packets. Therefore, it would be really helpful to dynamically adjust the values of SO and BO based on the traffic load. An investigation is conducted to determine the impact of MAC parameters such as BO and SO [101]. The performance of IEEE 802.15.4 MAC protocol using the Dynamic Manet On demand (DYMO) protocol is evaluated where the values of BO and SO were dynamically adjusted based on traffic loads. The attained results indicate that as the data rate per packet increases, the throughput drops dramatically. Moreover, for all values of BO = SO, the throughput is noticeably low. Superframe Adjustment and Beacon Transmission (SABT) is proposed to solve the beacon collisions (collision with each others and with data frames) [62]. he accurate values are assigned to BO and SO of PAN coordinator, cluster coordinator and sensor devices in cluster tree topologies. The results from analytical and simulation-based studies show higher successful transmission and lower energy consumptions in comparison with bare IEEE 802.15.4 standard. It must be noted that the length of active period for the PAN coordinator is fixed and is configured to cover the whole BI (SO = BO). Although the proposed approach has significantly improved the sensor network performance gains, such approach is designed for cluster-based tree topologies and may not be applicable on random independent neighbouring WSNs. Figure 2.7 depicts the process of SABT in the form of a flowchart.

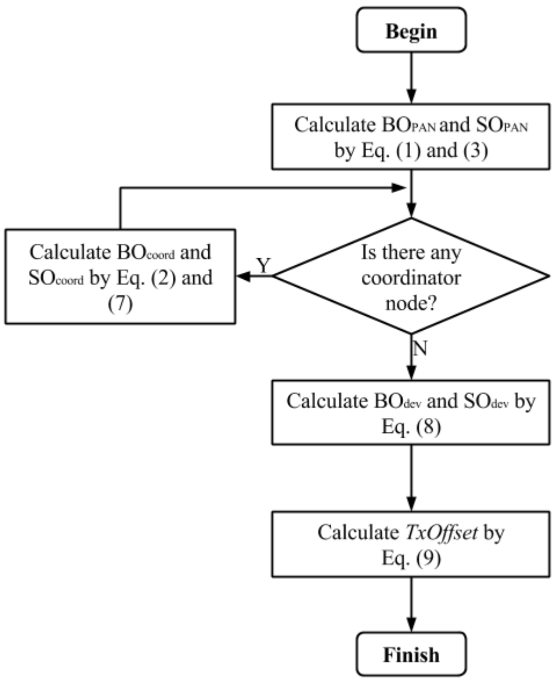


Figure 2.7: The SABT flow process

Another application that seems to be useful for initial configuration of IEEE 802.15.4 X-MAC parameters is *pTune*. pTune is a layered model designed to receive the network requirements such as network life time, end-to-end reliability and end-to-end latency as inputs and offers the optimised values for IEEE 802.15.4 X-MAC parameters [126].he proposed model responses to occurrence of some issues such as insufficient bandwidth, energy consumption as the peak traffic loads, traffic loads fluctuation and poor link quality by adjusting the X-MAC parameters values. However, how they could manage to accomplish the mentioned responses is not discussed in their article. Figure 2.8 depicts the pTune framework. Figure 2.8 depicts the pTune framework.

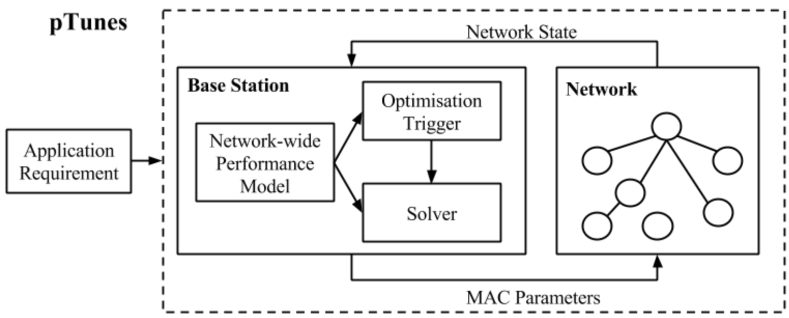


Figure 2.8: The pTune framework

The presence and absence of hidden terminals could also play a key role in the overall performance gains. The impacts of IEEE 802.15.4 MAC parameters namely: macMinBE, macMaxBE, macMaxCSMABackoffs and frame re-transmission on MAC protocol performance are analysed in [99, 100]. In their study, the traffic loads and the interference caused by neighbouring nodes varied in the presence and absence of hidden terminals. The objective of their study was to determine the proper values for MAC parameters in order to come up with the acceptable level of trade-off between success rate and the latency for the given range of the traffic loads. They have shown that at the lower traffic loads and the absence of hidden terminals, increasing the BE value could result in the lower packet loss rate. Moreover, higher collision probability and packet loss rate would be experienced as the number of hidden terminals becomes larger for all values of “macMaxBE”. According to the frame re-transmission results, it could be observed that any increase in frame re-transmission value beyond 1 does not cause any noticeable changes in the packet loss rate in the absence of hidden terminals.

A hardware-experimental is conducted to evaluate the performance of IEEE 802.15.4 [64]. The effects of four elements on the performance gains of IEEE 802.15.4 were determined. These four elements and parameters are as follows: 1) direct and indirect data transmission; 2) CSMA/CA; 3) data payload size and 4) beacon-enabled mode. The sensor devices and the coordinator formed a star topology where the sensor device 1 continuously sends and receives packets to and from the coordinator and the other three sensor devices are the traffic load generators. Figure 2.9 depicts the designed star topology.

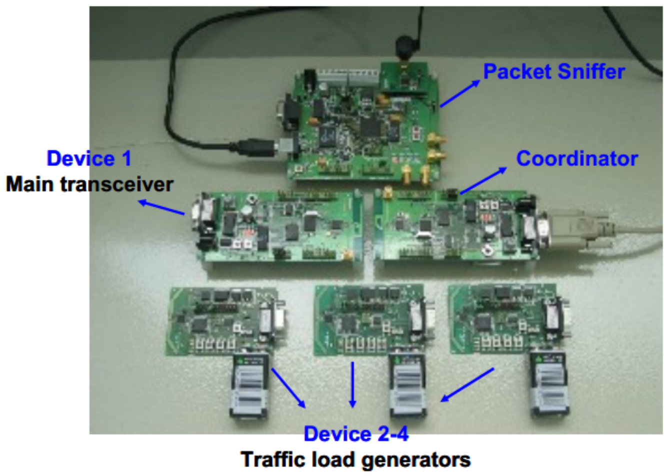


Figure 2.9: The star topology of the experiment conducted in [64]

According to their obtained results of the non-beacon-enabled mode, the indirect data rate (the transmission from coordinator to sensor device 1) is noticeably below the direct data rate (from sensor device 1 to the coordinator). This is mainly due to the sensor devices polling rate (sending request periodically). The second set of results shows the impact of low macMaxBE and macMinBE values: 4 and 3, respectively. It is shown that as the number of active devices becomes larger, the delivery ratio will be decreased because of data packet collisions. Moreover, with the larger traffic loads being transmitted by other devices, the delivery ratio shows the downward trend. This is again due to possibility of the collision occurrence. The impact of data payload size on the performance gain is determined in the third experiment. The result shows that as the payload size increases, the delivery ratio is decreased because of higher probability of collisions. In all conducted experiments, the BO = SO = 15 that represents the non-beacon-enabled mode. However, according to the last experiment that determined the effect of beacon-enabled mode, the values are both BO and SO varied from 1 to 15. The delivery ratio of the data packets is not considered in their obtained results, and only the effective data rate diagram is shown. It is then concluded that the non-beacon enabled mode experience higher effective data rate.

Duty cycle is also considered as one of the effective system parameters on WSN performance gains. "Reinforcement Learning" method is offered in [32] to determine the best duty cycle of the particular BI. This is accomplished by using the information (network statistics) collected by Duty Cycle Learning Algorithm (DCLA) during each active period. The aim of the proposed algorithm is to minimise the human intervention for re-configuring the duty cycle in order to fulfil the specific requirements of different networks. The results indicate that although Adaptive MAC for Efficient low-power communication (AMPE) proposed in [7] selects the same duty cycle as DCLA does, more processing overhead is incurred on micro-processor as it carries out more frequent CCAs. According to the AMPE algorithm, it is assumed that the duration of time that a channel is busy associates to the superframe occupation and is totally related to the traffic load factor. Therefore the amount of time that the channel is busy (during the active period) could be determined using the Physical Layer Management Entity - Clear Channel Assessment (PLME-CCA) request primitive offered in IEEE 802.15.4. However, this primitive requests are required to be invoked by sensor devices repeatedly within superframe duration. Although, CCA measurement seems to provide more accurate information rather than the estimation-based strategies, considering each CCA measurement lasting only eight symbols, results in noticeable energy consumption in sensor devices. This makes this approach less interesting. For more detailed information about the network performance comparison between DCLA and other schemes that deal with duty cycle, such as Beacon Order Adaptation Algorithm Beacon Order Adaptation Algorithm (BOAA) proposed in [87], and Duty Cycle Algorithm (DCA) proposed in [46] to enhance the IEEE 802.15.4-based MAC protocol please refer to [32]. The BOAA scheme uses certain number of transmitted message by the sensor devices in order to estimate the network offered load. Such received messages are maintained in the form of matrix which infers memory occupation and becomes problematic when dealing with large networks. However, the DCA exploits extra information such as transmit queue occupation and end-to-end delay in their duty cycle in order to determine the proper duty cycle. The queue indicator is injected in all frames and is used to determine the queue occupation during the active period. This approach. however, does not consider the transmission requests as the queue occupation in end devices decreases throughout the active duration. Table 2.3 briefly provides the information related to the major system parameters, the performance measures and the evaluation method and tools according to each and every of aforementioned state of the art.

Several surveys can be found that address the challenges and probable solutions in the area of WSNs/WBSNs/WBANs [25, 26, 85]. Some of them provide readers with the general overview of application, functional and technical requirements of the BAN [22, 90]. Some other surveys highlight present the overview of the characteristics and limitations of the sensor nodes that are commonly deployed in the WBSNs [40].

Many surveys have focused on the application point of view with the special emphasis on medical and health-related aspects. They have also revealed the issues encountered by healthcare systems [14, 88, 107, 111]. For instance, patient-mobility could be considered as a potential issue in the hospital while wearing a WBSN. Therefore, Caldeira *et al.* have surveyed the handover strategy for intra-mobility

Table 2.2: The analogy of State of art in terms of utilised system parameters

	System parameters and factors	**Performance Measures**	**Evaluation Methods and Verification Tools**
[91]	BI and packet transmission retries	energy consumption, packet loss ratio, medium access delay	OPNET simulator
[39]	number of transmitter in homogeneous and heterogeneous networks	end to end delay, goodput	OPNET simulator
[54]	slotted CSMA/CA algorithm, BO and SO	throughput and average delay and probability of success	analytical modelling
[89]	slotted CSMA/CA algorithm	throughput, average delay and probability of success	Markov model and ns_2 simulator
[96]	saturated and unsaturated sensor nodes in beacon-enabled and non-beacon enabled modes CSMA/CA internal parameters	CSMA/CA performance	analytical modelling (Markov model) and (Monte-Carlo simulation procedure)
[73]	packet arrival rate, number of stations, the finite size of individual node buffers, packet size, inactive period between the beacons and CSMA/CA internal parameters	average access delay and throughput	analytical modelling (Markov model)
[74]	packet arrival rate, number of stations, station buffer size, packet size and inactive period between the beacons	probability of access, probability that medium is idle, queue length distribution in the device, and probability distribution of the packet service time	analytical modelling (Markov model)
[66]	number of sensor nodes and CSMA/CA algorithm	throughput and MAC service time	analytical modelling (Markov model)
[63]	network size and CSMA/CA internal parameters	packet-arrival ratio, the probability of data packet, average service time, throughput and success rate	analytical modelling and C++ language based simulation code
[115]	slotted and unslotted CSMA/CA mechanisms and integration of the node and the channel	collision probability and throughput	analytical model and OPNET simulator
[125]	modified slotted CSMA/CA mechanisms	latency and delay, energy efficiency and throughput	analytical model (Markov model) and ns_2 simulator
[103, 104]	number of nodes and CSMA/CA mechanism	Energy efficiency of CSMA/CA algorithm and throughput	analytical modelling and C++ language based simulation code
[9]	ack and non-ack mode with both saturated and unsaturated traffic pattern, CSMA/CA mechanism	throughput, average delay, collision rate, buffer occupancy and offered load	bespoke simulation platform
[10]	number of nodes, slotted CSMA/CA algorithm	throughput, average MAC service time, successful transmission and energy consumption	Analytical Model (Markov model) and A particular simulator designed by author
[119]	number of sensor devices, different priority levels for different sensor devices (service differentiated) and adaptive CSMA/CA internal parameters values	average delay, effective data rate, and packet loss rate	IEEE 802.15.4 module included in the OMNeT++ simulator
[67]	number of sensor devices, different priority levels for different sensor devices (service differentiated) and adaptive CSMA/CA internal parameters values	collision probability and mean end-to-end delay	IEEE 802.15.4 module included in the OMNeT++ simulator
[5]	number of sensor devices, power management mechanism (always active or not), periodic or poisson packet arrival patterns, frame re-transmissions, BI, CSMA/CA parameters	delivery ratio, latency, on-time delivery ratio average energy per packet	Gilbert-Elliot model and ns_2 simulator and real test-bed experiment

where the sensors are able to move around within the same network domain but different access points [20]. Carrano *et al.* have focused on the energy consumption

Table 2.3: The analogy of State of art in terms of utilised system parameters, cont.

	System parameters and factors	Performance Measures	Evaluation Methods and Verification Tools
[99, 100]	macMinBE, macMaxBE, macMaxCSMABackoffs, frame re-transmission,traffic loads and interference caused by neighbouring nodes	packet loss probability and the packet latency	Simulink or NS-2 and the real test-bed experiment
[126]	low and high traffic loads varying link quality and generally MAC parameters	network lifetime, end-to-end latency and end-to-end reliability	test-bed experiment
[64]	the direct and indirect data transmissions, CSMA-CA mechanism, data pay load size, and beacon-enabled mode	data throughput, delivery ratio, and RSSI	real test-bed experiments
[62]	inter-arrival time	probability of successful transmission, the probability of collisions, network gudput and energy consumption	Markov model and ns_2 simulator
[32]	network offered load, number of sensor devices and duty cycle	energy efficiency, end-to-end delay and probability of successful transmission	OPNET simulator
[7]	SO and the traffic-load factor	efficiency of the proposed algorithm, throughput, and coordinator energy consumption	Network Protocol Simulator (NePSing)
[87]	BO, time scale,	the average power consumption to the power consumption in receive mode, service delay and BO	Simulation (not specified)
[46]	number of sensor devices	energy consumption(sensor and coordinator), SO variance, number of packet dropped, end-to-end delay and successful transmission	ns_2 simulator

of the sensor nodes through managing the duty cycle [24], while Sudevalayam *et al.* have considered the applicability of the energy harvesting techniques on WBANs using the human body as the source of energy [105]. Khanafer *et al.* have focused on some strategies to mitigate the impact of interference on performace gains [49]. However, in contrast to the above-mentioned surveys, this paper specifically deals with the internal interference caused by neighbouring WBSNs. More particularly, the impact of system parameters on WBSN's performance gain is investigated from two perspectives: MAC parameters and protocol design. Furthermore, a simulation study has been conducted to clarify the impacts of MAC parameters on WBSN's performance gain in the presence of intensifying internal interference.

3 System Model

In this chapter, the system model considered in our simulation study is explained. More specifically, there is a brief discussion about the simulation platform (network simulator) followed by a detailed explanation of the simulated network scenarios and the deployed network topology. Thereafter, the considered model for WBSN is explained along with the performance metrics considered in this thesis.

3.1 Simulation Platform and Tools

Network simulators are widely utilised in order to test and evaluate ideas and developed schemes. One of the suitable network simulators is an open source network simulator called **Castalia** which has been considered in this thesis [16]. This network simulator uses Object-oriented Modular Network Simulator (OMNET)++ as its operating platform. Please note that other network simulators either were not available as an open-source network simulator or the access to their source code was limited e.g. Optimised Network Engineering Tool (OPNET) [75] and QualNet [97]. We simply discarded other open source network simulators such as ns_3 mainly due to higher higher level of debugging complexity.

Castalia (version 3.2) is a parametric network simulator that is generally designed for networks with low-powered embedded devices, specifically for wireless sensor networks. Being parametric allows users to easily modify and develop protocols. This network simulator is based on the OMNeT++ platform and can be utilised to test and evaluate algorithms and protocols while benefiting from the realistic wireless channel and radio models. The major features of this network simulator are as follows:

- A channel model based on experimentally measured data.
- A radio model based on commercially available radios for low-power communication.
- Models for CPU power consumption and the clock-drift of nodes.
- A range of MAC and routing protocols.
- Designed to support modification and try new algorithms/protocols.

Castalia is generally designed for typical sensor devices and is not sensor platform-specific. This network simulator is a framework that has been designed and developed to validate an algorithm/protocol before proceeding to implementation on a specific sensor platform. The modules and their connections in Castalia are shown in Figure 3.1

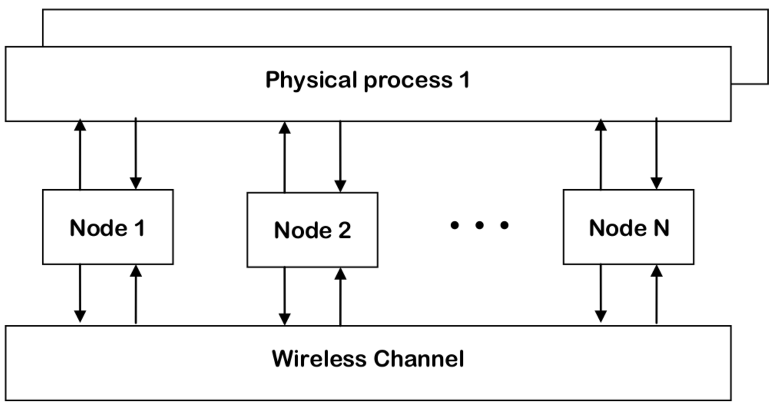


Figure 3.1: Castalia module architecture

The nodes do not connect to each other directly, and the wireless channel is used for communication between nodes. The arrows represent message passing from one module to another. A Packet is firstly sent to the wireless channel which then decides the destination of the packet. There are physical processes that nodes are meant to monitor and through which, nodes are also linked to each other. More specifically, for every physical process, one module exists in order to maintain the "quantity" that the physical process is representing. The nodes retrieve the physical process information in time and space via sending a message to the associated module in order to get their sensor readings. A node can have multiple physical processes, representing multiple sensing devices or multiple sensing modalities. For more information about the node module architecture please see Castalia architecture in [16].

3.2 Simulation Scenario and Topology

In this thesis, an individual WBSN forms a star topology which consists of one coordinator and four sensor nodes. Each of the four sensor nodes has a distance of 1 m to the coordinator. No further attenuation – e.g. the shadowing effect caused by the human body can impose substantial additional path-loss in the order of 30 - 35 dB therefore, for IEEE 802.15.4, it is often required to use the largest possible transmit power [57, 61] – is considered in this research. Moreover, it is assumed that there is no external interference caused by other technologies. These assumptions allow us to attribute all packet losses to packet collisions and not to path loss or hidden-terminal situations. In the simulation scenario, all WBSNs are located on the same spot. In our simulation experiments, the number of WBSNs is varied to determine the impact of WBSN-density on our main performance measures. Additionally, all nodes utilise the same transmit power and the impact of different transmit power settings is largely ignored by locating all WBSNs at the same spot. Using these settings, allows us to explain the observed performance because of the direct impact of internal interference experienced by WBSNs and no other effective factor.

The activation time for each WBSN is drawn randomly and independently from an exponential distribution with a mean value of 1 second. More specifically, both coordinator and sensor devices become active simultaneously at a particular random time, except for static-idealized scheme (explained later in detail). This configuration allows us to avoid phase synchronisation and creates more generic environments where sensor nodes are activated arbitrarily. We also assume that the individual nodes can have clock drift. More specifically, the drift for each node is drawn from a zero-mean Gaussian with a standard deviation of 30 Îijs.The clock-drifting is not used for two schemes, namely: static-idealized and static-random where WBSNs stick to their initial phase distribution throughout. However, it is considered for other proposed schemes where WBSNs and are able to change their phases and operating frequency whenever required. This is achieved by utilising specific functions (setTime and cancelTimer) in Castalia that automatically trigger the clock-drifting function.

3.3 WBSN model

A WBSN operates in a beacon-enabled mode. Since (the values of) the beacon order and the superframe order determine the length of the BI and the CAP, it is presumed that these values could strongly influence the WBSN performance. Therefore, the values of beacon order and superframe order are both varied in a particular part of our simulation experiment (see Table 5.1 and section 5). However, in other parts of this thesis the values of these system parameters are fixed (see Table 3.1). In our simulation study we only consider uplink packets. Uplink packets are the ones that are transmitted from a sensor device to its associated coordinator. No downlink packets are considered in our simulation study except for acknowledgement packets and the beacon packets. In fact, uplink packets and downlink packets are different and to understand the performance of WBSNs most clearly, it is better to avoid the mixture of uplink and downlink packets. The mixture of uplink and downlink packets would require us to understand which part of the performance difference is due to mixing of the uplink and downlink packets and this would only add unnecessary complications to the understanding the performance of WBSNs. All uplink packets are transmitted during the CAP, and the GTS slots are not set in the simulated superframe structure. Yazdi *et al.* have shown that the lack of carrier-sensing GTS slots in the presence of interference would lead to severe performance degradation in terms of successful packet transmission [121]. Their research motivated us to ignore the GTS in the simulated superframe structure in the beacon-enabled mode.

In our simulation scenarios, the sensor devices first associate with the coordinator upon receiving the beacon packet with the correct MAC address (correct PAN-ID field in the beacon packet). For some schemes the coordinator initially performs the channel scanning procedure to find the best channel. The best channel is defined as the channel with the smallest number of occupants which results in lower probability of experiencing mutual interference due to lower ratio of the occurrence of the overlapping active periods. Therefore, the sensor devices would initially become orphan in the early stages. An orphan sensor device scans the whole frequency spectrum to find its associated coordinator (via scanning each channel in order to find the beacon packet with the correct PAN-ID). Please note that we assumed the sensor device knows the BI and scans each channel for the duration of a BI before switching to other channels. This means that no particular coordinator discovery algorithm is performed by the orphan sensor device.

Data packets are generated periodically as soon as the sensor device is associated to the coordinator. The interval of generating the data packet is generally determined by the application layer. Thereafter, at the MAC layer, the proper values – e.g. the largest BI that does not exceed the application period – will be assigned to the beacon order and superframe order in such a way that the application requirements are satisfied. This means that the data packet generation and the value of beacon order are strongly tied up together. However, in order to determine the impact of data packet generation rate on the WBSN performance, it was necessary to decouple the value of beacon order from the data packet generation ratio. The data packet generation ratio is also varied in our experiment (see Table 5.1 and section 5). In all other parts of this thesis the value of beacon order strongly depends on the data packet generation ratio and being calculated using Equations 2.2 and 2.1 in section 2.1.

The payload size of the data packet is fixed to 64 bytes. When the coordinator successfully receives a data packet (sent by the sensor device), it responds with sending an acknowledgement packet immediately. If the sensor does not receive the acknowledgement packet (sent by the coordinator), it re-transmits the data packet and keeps performing the re-transmissions for a limited number of times. Rohm *et al.* have shown that the probabilities of successful transmission of data packets do not significantly change after 3 transmission re-tries [99]. In this thesis, it is assumed that for the reliability-oriented applications, one would at least perform 3 re-transmissions. If all re-transmissions have been exhausted without receiving an acknowledgement, the packet will be counted as a failure and will be added to the number of packet losses, otherwise, it will be considered as a successfully transmitted data packet. Please note that when the sensor device becomes orphan, the application layer continues to generate data packets periodically, regardless of the sensor device status (orphan or connected). Therefore, IEEE 802.15.4 offers another parameter called "packet validity time" within which, the sensor device should receive the acknowledgement packet from the coordinator, indicating the successful transmission of the data packet. In this thesis the packet validity time is configured to four times the beacon period. If the sensor device does not receive the acknowledgement from its associated coordinator within the packet validity time, the data packet will be dropped from the MAC buffer and that data packet is counted as failure. Although there is no dependency between the packet validity time and the number of re-transmissions in terms of configuration settings, there is actually a logical dependency between these two parameters. The data packet is re-transmitted as long as it is queued up in the MAC buffer. This means that as soon as the packet validity time expires, the re-transmission counter will be reset for the next data packet in the MAC buffer queue. Since transmission retries above 3 does not play a significant role in the successful transmission of data packets, the packet validity time is set to four times the beacon period and after this time the packet will be discarded. In all conducted simulation experiments in this thesis, the sensor devices keep track of the beacon packets (sent from their associated coordinator) to maintain their synchronisation. If the sensor device has not received four consecutive beacon packets, it becomes orphan. The orphan device reacts according to the deployed scheme: in those schemes where a WBSN always operates on the same operating frequency the orphan sensor device will search for beacon packets on the same operating frequency as it were before. However, in schemes which allow dynamic and on-going changes of the centre frequency, the orphan sensor device needs to assume that its WBSN might have switched to another operating frequency (the channel with the smallest number of occupants) and scans all channels in round-robin fashion to re-discover its coordinator. Table 3.1 shows the values of all parameters which are kept fixed in this thesis study. Generally the simulation time is set to 3000 seconds unless stated otherwise. For example the simulation time is set to other values in order to fulfil the requirements of the particular simulation studies e.g. 5 sensitivity analysis.

3.4 Static and Dynamic Environments

In the static environment, it is assumed that all the WBSNs are constantly switched on throughout and furthermore, they are not synchronised. This means that, two WBSNs whose active periods overlapped on each other will experience mutual interference for the rest of simulation time. We have also considered a generic scenario in

Parameter	Value
Network Setup	
Layout of one WBSN	One coordinator, four sensors on a circle of 1m radius around coordinator, beaconed mode
WBSN location	all on the same spot
Number of WBSNs	all WBSNs configured identically, number varied in $\{50, 100, 150, 200, 250\}$
Channel model	log-distance [98], no shadowing, no external interference, no hidden-terminal situations
Application Layer Parameters	
Data payload	64 byte
Packet Inter-arrival Time	$0.01536s \times 2^{BO}$ sec
Coordinator start up delay	Exponential distr. 1sec
Packet validity time	$4 \times$ BI
macMinBE	3
macMaxBE	5
MAC Layer (CC2420) Parameters	
MAC Buffer size	16
Max. number of retransmissions	9
Physical Layer (CC2420) Parameters	
Transmit power	-25 dBm
Data rate	250 kbps

Table 3.1: Fixed parameters

which multiple WBSNs continuously leave the frequency spectrum and then again start utilising it after a while. We call it *dynamic-environment*, as WBSNs are continuously switched off and on during the simulation time. Dynamic environment is designed to emulate mobility / dynamic population of WBSNs.

In our simulated dynamic environment, a WBSN is forced to switch off after a random time selected uniformly from [500 BP, 1000 BP], where BP is the Beacon Period (in seconds). It is switched back on after a random time selected uniformly from [400 CAP, 600 CAP]. The CAP duration is chosen to make sure that WBSNs switch back on in other phases. Shifting the CAP could be beneficial for the schemes in which phase-shifting does not occur. Please note that in the dynamic environment, when a WBSN is switched back on, its operating frequency is determined randomly if a scheme with frequency-hopping capability is used. The same channel with a new randomly (uniform distribution) chosen phase is used in the case of a scheme without the frequency-hopping capability. In our simulation-based experiment, the performance of the proposed schemes being deployed in the dynamic environment is evaluated in Section 7.2.

3.5 Performance Measures

In this thesis we considered two sets of performance measures: **primary** performance measures that are geared towards applications that have some notion of “acceptable” and “unacceptable” performance, e.g. in terms of packet losses for regularly transmitted sensor signals. Primary performance measure includes the *success rate*, *satisfaction rate* and *carrying capacity* and **secondary** performance measures that includes the *energy consumption* (the sensor device and the coordinator, individually) and the *orphan period*.

3.5.1 Primary performance measures

Before explaining the primary performance measures, it is required to become familiar with the term *satisfaction*. An individual WBSN is regarded as *satisfied* if the average successful transmission of the data packets is 95% or more. As mentioned before, within the WBSN, the data packet is considered as successfully transmitted (from sensor to the coordinator) if the originating sensor device received the corresponding acknowledgement from its coordinator. The *satisfaction rate* is defined as the percentage of the satisfied WBSNs (WBSNs that are experiencing over 95% success rate) out of the given total number of WBSNs. Since all available operating frequencies are utilised by all WBSNs, to experience the internal interference in each channel, it was essential to locate a sufficient number of WBSNs on each channel (see Table 3.1). For instance, when the total number of WBSNs is 250, this means that 250 WBSNs are uniformly distributed over 16 operating frequencies (which is $\approx$ 16 WBSNs in each channel). Please note that in the real life occasions not all 16 operating frequencies are available due to sharing the frequency spectrum with other technologies.

The second primary performance measure is the *carrying capacity*. For the given scheme, the carrying capacity is defined as the number of WBSNs that can be located on the same spot in such a way that at least 95% of them are satisfied. In order to obtain the carrying capacity, a given scheme is simulated with the WBSN number taken from the set Δ. For each $\delta \in \Delta$, at least 64 simulation runs (replications) are executed to reach a relative confidence interval half-width of 5% at a confidence level of 95% for the success rates. For each simulation run, the number of satisfied WBSNs is calculated. Thereafter, the average of these numbers over all simulation runs is calculated which provides us with the average percentage of satisfied WBSNs for the given $\delta \in \Delta$ of WBSNs. When all the averages for all $\delta \in \Delta$ have been calculated, a second-order polynomial regression curve is deployed to interpolate the average number of satisfied WBSNs between the given points in Δ. Finally, the carrying capacity is calculated as the point where the regression curve crosses the 95% line.

In addition to these two performance measures we will also show results for the average packet success rate of WBSNs, where as above the average packet success rate of an individual WBSN is the average packet success rate of all the uplink data packets sent by the four (equally loaded) sensors of a WBSN, and the (overall) average success rate is the average of the success rates of all WBSNs. This is interesting for applications which do not have a natural threshold for acceptable packet loss performance but are able to degrade gracefully with increasing packet loss rate[1].

[1] It is meaningful to talk about the success rate of a WBSN as all sensors are configured identically

3.5.2 Secondary performance measures

The secondary performance measure focuses on the life time of a wireless body sensor network. More specifically, the amount of energy consumed by both coordinator and sensor devices is measured individually. In this thesis we have introduced two performance measures that are closely associated to the wireless body sensor network's life time, namely: *fraction of time without PAN coordinator* – or *orphan period* – and *energy consumption*.

The first secondary performance measure is the *fraction of time without PAN coordinator* or *orphan period*. When a sensor device loses four consecutive beacon packets, it becomes orphan. The orphan sensor device has to scan either the whole frequency spectrum (for adaptive schemes) or the current channel (non-adaptive schemes) to find the associated coordinator. Performing scanning procedure in order to find the corresponding coordinator consumes a great deal of energy and such energy consumption is directly related to the amount of time a sensor device has spent in orphan state. The fraction of time that the sensor device is orphan is considered as the orphan period of that sensor device. The average of the orphan periods of all sensor nodes (in all simulation replications) is considered as the fraction of time without PAN coordinator or orphan period.

Since WBSNs are energy-constrained low-powered systems, energy consumption is also considered as an important performance measure. The sensor device consumes energy to perform all the given tasks, e.g. scanning the channel(s) to find its coordinator, competing with other sensor devices to deliver the data packets to the correspondent coordinator, and for adaptive schemes, some amount of energy is consumed for channel switching purpose, sensing and computations. The energy consumption of coordinators, however, is not as important as that of sensor devices. We can assume that the coordinators have batteries with larger capacities. For the proposed Active scheme and adaptive passive schemes, the coordinators have to continuously scan the frequency spectrum and keep track of the best operating frequency (in terms of the smallest number of detected beacon packets). Performing such scanning task results in higher energy consumption compared to other proposed schemes. However, later on we show that achieving higher satisfaction rate and channel capacity can be achieved at the higher energy consumption of coordinators for Active schemes and adaptive passive schemes. The energy models employed in our simulation and implementation studies are elaborated in subsection 3.5.3.

3.5.3 Energy model

One of the main concerns in the field of WBSNs is the energy consumption of sensor devices due to energy constrains. Therefore, energy consumption is considered as one of the major performance measures to evaluate the considered schemes. In our simulation study, the energy consumption (power consumption) of a sensor device is related to its transceiver (as elaborated in [18, 94, 95]) and the power consumed by other components (e.g. sensors and micro-controllers) of WBSN nodes is ignored. The energy consumed by the transceiver is modelled using the characteristics of the IEEE 802.15.4 compatible ChipCon CC2420 transceiver [28]. It is assumed that the power supply voltage and the transmit power are fixed to 3.3 V and -25 dBm, respectively. In our simulation study, there are three operational states in a single sensor device: sleep, transmit and receive states. The time spent in either of these operational states is collected individually. Thereafter, the collected time is multiplied with the average power consumption of that particular state to compute the total energy consumption. Energy consumption levels of both coordinators and sensors are individually measured and given in Joules using the following formula:

$$P_i = C_i \times V_i. \tag{3.1}$$

Where power consumed (P_i) at a given transceiver equals to current drained from the battery (C_i) at the specific state i, multiplied by the voltage of the battery V_i.

The physical layer is responsible for managing the transition between the different transceiver states (Receive, Transmit and Sleep state). In this thesis, since we have ruled out the impact of transmit power on WBSN performance by locating all WBSNs at the same spot, the transmit power is fixed to -25 dBm for our simulation-based study. Table 3.2 shows the power consumption in each state. All sensor devices *sleep* during the inactive period and the behaviour of the coordinator depends on the employed scheme: in schemes where the coordinator is supposed to keep track of the best channel (for future channel switching), it changes its current state to *receive* state and scans the frequency spectrum; in other schemes, the coordinator performs its routine tasks and sleeps during the inactive period. For more information about the frequency-scanning procedure please see [76, 77] and Chapter 4. When a sensor device has any data packet to transmit, it changes its current state to *transmit* state and sends the data to the coordinator. The same change to the transmit state occurs when a coordinator sends beacon packets at beginning of the superframe. If the sensor has no (other) data to transmit to the coordinator it changes its current state to sleep state.

CC2420 Parameter		
Receive (RX) mode	3.3 v * 19.7 mA	65.01 mW
Transmit (TX) mode -25 dBm	3.3 v * 8.5 mA	28.05 mW
Sleep mode	3.3 V * 20 μA	0.066 mW

Table 3.2: CC2420 parameter specification.

4 Considered Schemes

In this chapter, the considered schemes are described in detail. These schemes art designed using ”distributed system architecture“. The ”centralised system architecture“ is not chosen in this thesis due to several reasons: 1) Avoiding introduction of a central entity that controls affairs related to WBSNs e.g. the operating frequency, start the activity in a particular time slot, collecting data related to absence or presence of a WBSNs in a specific time slot and so on. 2) As the number of WBSNs become larger in the frequency spectrum, the communication between the central entity and a target WBSN is highly likely to fail due to higher probability of packet collisions. This will eventually degrade the performance of WBSNs as a whole. 3) While understanding that designing a protocol for wireless sensor networks is highly application-specific, the distributed system architecture enables WBSNs to be more flexible in terms of having different duty cycles and highly self-deployed. Therefore, we have chosen distributed system architecture to design protocols and algorithms in this thesis. The considered schemes are categorised into two main categories, namely: *Passive* schemes, where there is no communication between WBSNs; *Active* schemes, where WBSNs communicate with each other in order to collaboratively utilise the shared resources (those WBSNs that are using the same operating frequency). Passive schemes, depending on their channel switching capability, are further divided into *static* and *dynamic* schemes.

4.1 Passive Schemes

The term ”passive“ refers to schemes in which no communication nor any information exchange occur between WBSNs whatsoever. In this category, some schemes remain in their original operating frequency throughout and some others are actually able to switch to other operating frequencies when two conditions are met: the packet loss rate exceeds a given threshold, and there is another operating frequency with smaller number of occupants[1]. Depending on the channel-switching capability, the passive schemes are further categorised into two main groups, namely: static schemes, where the WBSNs in a particular operating frequency will remain there throughout; dynamic schemes, where the WBSNs can pick another operating frequency (either randomly or according to some measurements) and hop there if the conditions are met.

4.1.1 Static Schemes

The common characteristic among the static schemes is that a WBSN is not able to change the operating frequency or phase dynamically, and they will remain in the original operating frequency throughout:

static-random scheme: In this scheme, the WBSN is assigned a particular operating frequency autonomously and randomly according to the uniform distribution. The WBSN stays in that operating frequency throughout. WBSNs employing the static-random scheme do not perform any measurement. Since the coordinator does not change the operating frequency, an orphan sensor only needs to scan the original operating frequency to find its associated coordinator (receive the beacon packet with its associated coordinator PAN-ID) and does not scan any other operating frequencies. The start-up times for the WBSNs are drawn randomly and independently

[1]The number of occupants alone is not noticeably interesting compare to the overall load (channel utilisation). However, since all WBSNs are equally loaded, the number of WBSNs can be assumed as equivalent to the overall load or channel utilisation. It is a possible outcome of future work to develop schemes that reasonably estimate the overall load.

from an exponential distribution with a mean value of 1 second, according to the system model. This scheme is considered as one of the baseline schemes that represents the lower band of the achievable performance. Figure 4.1 shows the state machine diagram of this scheme.

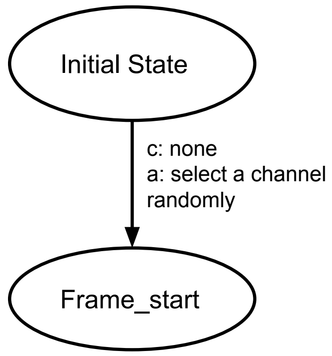


Figure 4.1: State machine diagram of static-random scheme

Please note that the "Frame_start" state in all Figures refers to the state when a WBSN transmits the beacon packet routinely, and the CAP starts immediately after the beacon transmission.

static-initial-choice scheme: In this scheme, the coordinator of a WBSN scans the whole frequency spectrum in order to find the operating frequency with the smallest number of occupants, and stays in that operating frequency throughout. The frequency spectrum scanning procedure is performed at the initialisation time of the WBSN activation and channels are scanned in a random order. More specifically, once the WBSN is assigned an initial random operating frequency, it generates a random order for scanning the whole spectrum frequency and starts scanning all operating frequencies using that random order. The coordinator stays in each operating frequency for a beacon period to detect as many other beacon packets as possible and then proceeds to the next channel. This channel scanning procedure is repeated until all operating frequencies are covered. If the coordinator finds more than one channel with the same smallest number of occupants, it picks one of them randomly. Once the operating frequency is determined, the WBSN will stay there throughout. Figure 4.2 shows the state machine diagram of this scheme.

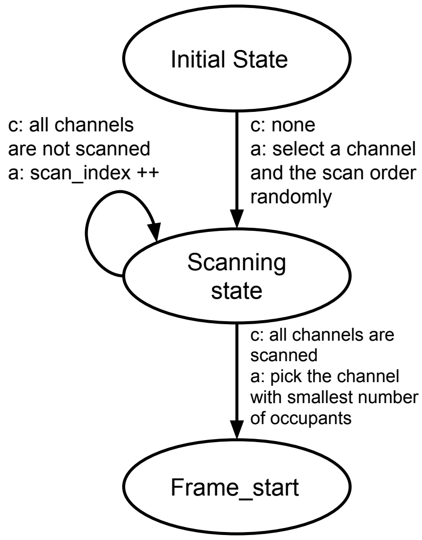


Figure 4.2: State machine diagram of static-initial-choice scheme

static-idealized scheme: This scheme is designed in such a way that we assumed a genie evenly distributed all WBSNs over all available frequencies and equally spread them over time within each frequency. More specifically, in this scheme, both the phase and the operating frequency of WBSNs are determined at the initialisation time. More precisely, WBSNs are equally distributed over all operating frequencies and time in such a manner that all operating frequencies carry (nearly) the same number of WBSNs. Furthermore, on each operating frequency the WBSNs are equidistantly spread over time (within a beacon period). This particular configuration is possible due to all WBSNs have the same configuration. In a more realistic scenario, the allocation of operating frequencies and time slots would perhaps seek to balance utilisation. Figure 4.3 sketches the formation of the WBSNs in a operating frequency before (Figure 4.3.a) and after (Figure 4.3.b) deployment of static-idealized scheme. Please note that Figure 4.3.b can be considered as the output of a centralised scheme.

Clearly, increasing the number of WBSNs would result in higher overlapping ratio of the active periods of the WBSNs placed in the same operating frequency. Hence, it becomes more likely to experience success rate degradation. Please note that in

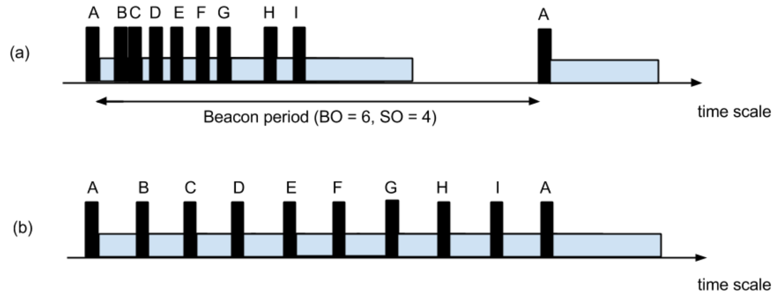


Figure 4.3: Before and after the employment of the static-idealized scheme

this scheme a WBSN is not allowed to change its operating frequency nor is able to shift its original phase (shifting beacons / superframe). In this scheme, it is assumed that the clocks on all nodes (both coordinator and sensor devices) are ideal and identical. In more realistic scenarios, clock-drifting would be experienced over time. In this thesis, it is hypothesised that this particular allocation of the frequency and time slot together with no clock-drifting will result in both the highest average per-WBSN packet success rate and carrying capacity. Therefore, this scheme is also considered as a baseline scheme which compared to other proposed schemes represents the upper band of achievable performance . Figure 4.4 shows the state machine diagram of this scheme.

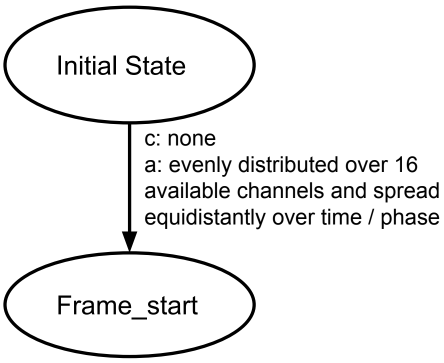


Figure 4.4: State machine diagram of static-idealized scheme

4.1.2 Dynamic Schemes

The term ”dynamic“ refers to those schemes in which a WBSN is able to change its operating frequency (but not phases) under the given conditions, e.g. the packet loss rate exceeds a given threshold (or conversely the success rate degrades below a given threshold) and there is another operating frequency with a smaller number of occupants. The channel switching can happen several times during the life time of an active WBSN. The passive dynamic schemes are categorised based on the way a new channel is determined. If the coordinator of a WBSN picks a new channel randomly, the scheme is called *dynamic-random-hopping*, and if it picks the new channel as a result of a measurement procedure, it is called the *dynamic-targeted-hopping scheme*. The dynamic-targeted-hopping scheme is further subdivided into Periodic Assessment (PA) and Continuous Assessment (CA). The considered passive dynamic schemes are explained as follows:

- **dynamic-random-hopping scheme**: In this scheme, the coordinator of a WBSN continuously examines the quality of the current operating frequency by measuring the packet loss rate – calculating the gap between the sequence number of two consecutive received data packets – and if it exceeds the (pre-defined) threshold (which is the packet loss rate of 5%), it chooses an operating frequency randomly using the uniform distribution and considering all channels except the current one. Then the whole WBSN hops to that particular operating frequency. The channel switching algorithm used in this thesis is inspired by the channel switching strategy described and used in [121]. More specifically, the coordinator of a WBSN informs its associated sensor devices about the new operating frequency by embedding this information in the beacon payload for four consecutive beacons. If a sensor device receives only one of these four beacons it will synchronise itself with the coordinator jumping time. We use ”Four“ consecutive beacons to increase the likelihood for the sensor device to receive at least one of these beacon packets.

In order to determine the packet loss rate (or the success rate), the coordinator uses the data packet sequence numbers and counts the gap between two successfully received data packets. The packet loss rate is calculated over a sliding window of 50 beacon periods. If the packet loss rate is within the given packet loss rate threshold, the window slides by one when the new data packet is received. Otherwise, a WBSN will switch to a randomly selected channel as described earlier. This procedure is continuously performed throughout. In this scheme if a sensor device becomes orphan, it has to assume that its associated coordinator has hopped to another operating frequency and hence it has to scan the whole frequency spectrum to find its associated coordinator. Please note that the packet loss calculation procedure introduced in this scheme is suitable when the data traffic rates are reasonably high. In some other case when there are larger spaces between generated data packets, an exponentially-weighted moving-average estimator could be the better option to calculate the packet loss rate. Figure 4.5 shows the state machine diagram of this scheme.

- **dynamic-targeted-hopping scheme / continuous assessment**: In this scheme the coordinator of a WBSN continuously scans other operating frequencies during its inactive period and in a round-robin fashion (one channel is scanned per beacon period). More specifically, when the inactive period starts, the coordinator jumps to a new channel and scans that channel to detect other beacon packets during the inactive period. By the time the inactive period is ends, the coordinator jumps back to its original operating frequency and resumes its routine activities. This procedure is continuously repeated to cover all operating frequencies throughout. Using this way, the coordinator keeps track of the operating frequency with the smallest number of occupants. When the packet loss rate (calculated the in same way as for dynamic-random-

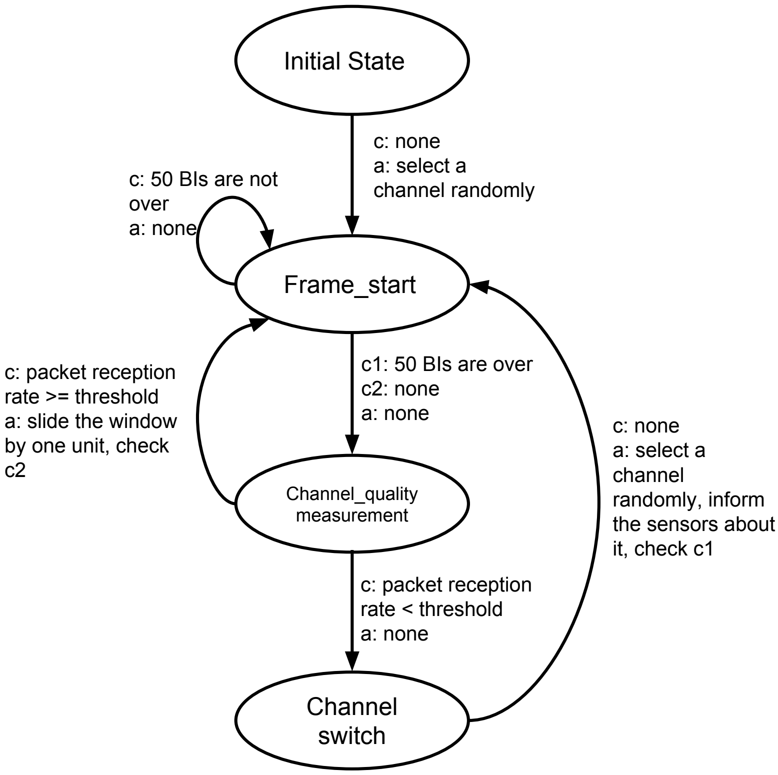


Figure 4.5: State machine diagram of dynamic-random-hopping scheme

hopping scheme) exceeds the 5% threshold and a better[2] channel is found, the coordinator includes the new channel in the payload of the beacon packet for four successive beacons, and switches to the new operating frequency, thereafter. In this scheme, the packet loss rate is calculated using the window of 50 beacon periods as described for dynamic-random-hopping scheme. Please note that if the coordinator has multiple operating frequencies with the same smallest number of occupants, it picks one of them randomly. If the sensor device receives at least one (out of four) beacon packets, it will synchronise itself with the coordinator‘s hopping time. Figure 4.6 shows the state machine diagram of this scheme.

- **dynamic-targeted-hopping scheme / periodic assessment**: The only difference between continuous assessment and the periodic assessment is that

[2]The channel with the smallest number of observed occupants with the difference of at least two WBSNs.

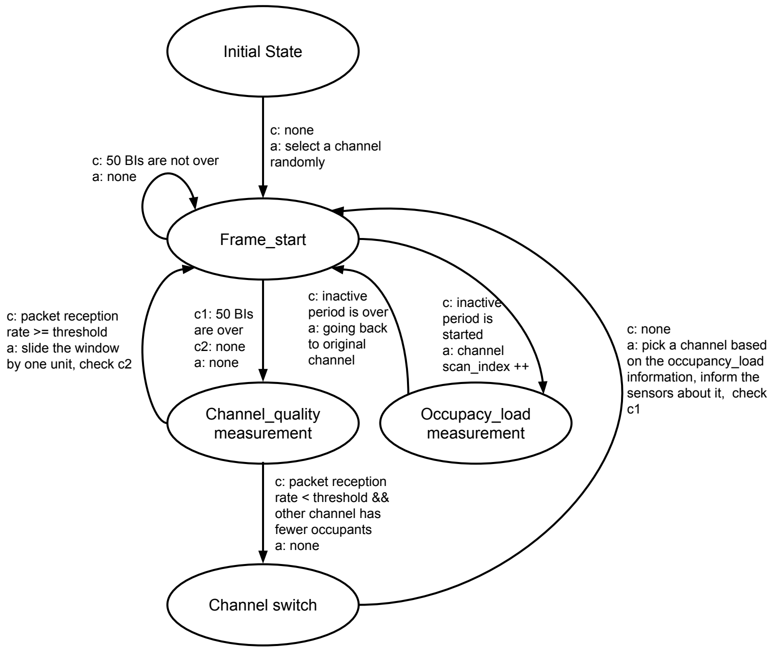


Figure 4.6: State machine diagram of dynamic-targeted-hopping scheme

in the continuous assessment scheme, the channel quality assessment (packet loss rate calculation) and keeping track of the best channel (the channel with the smallest number of occupants) are performed separately from each other. However, in the periodic assessment scheme, the coordinator assesses the channel quality every 50 beacon periods. Once the packet loss rate has exceeded the 5% threshold, the coordinator starts scanning the whole spectrum (only once) and picks the channel with the smallest number of occupants. Using this scheme, the coordinator does not have to continuously scan the whole operating frequency and hence, it can save more energy.

4.2 Active Scheme

The term "Active" suggests that there is a type of communication between networks (more particularly between coordinators). This communication can be shaped as command packet transmission or in our case including necessary information into the payload of its periodic beacon packet which would be accessible for all neighbouring

WBSNs. Using (the payload of) beacon packets and no other types of packets, for communication purposes is of important matters in a sense that the proposed scheme will be compatible with IEEE 802.15.4 standard MAC protocol, whereas adding an extra packet would only increase the chances of packet collisions or would lead to making wrong decisions in terms of channel hopping or phase shifting. In this thesis, the designed active scheme is called Dynamic Phase Shifting (DPS) and provides WBSNs with the opportunity of communicating with each other in order to utilise the current operating frequency more efficiently by finding a suitable time slot / phase in a particular operating frequency. In DPS scheme each coordinator of a WBSN includes some additional information into its periodic beacons which other WBSNs can use, and beyond this there is no active negotiation, no changes to other frame formats are required, and so on. We argue that such a scheme can be implemented in an IEEE 802.15.4 protocol stack without major changes.

In designing the DPS scheme we have aimed to reach two different goals: there should be no need for any kind of global consensus (e.g. having all nodes agree on the number of WBSNs present) and it should be completely distributed. As opposed to our previous research shown in [80, 84], the desire to not rely on consensus is based on the realisation that it will be very hard to achieve in scenarios with mobile WBSNs (where the set of WBSNs among which consensus is to be achieved is time-variable), in the presence of hidden-terminal situations or beacon collisions, and with nodes distributed in space in a heterogeneous fashion. Distributedness is desirable since more centralised solutions (like electing one leader who computes an allocation similar to the static-idealized scheme) require consensus, a substantial amount of signalling for collecting information and disseminating the schedule, and also require a substantial amount of new functionality to be added to WBSN coordinators.

In the DPS scheme, two algorithms are performed in parallel with a negligible interaction between them: the *frequency adaptation* algorithm and *phase adaptation* algorithm. To perform these algorithms, the coordinator of a WBSN includes some information to the beacon payload. This information is further used by the other nodes to inform each other about their views and to take proper actions accordingly. Two further decisions have driven the design of DPS scheme: because of the decentralized nature we have included randomized decisions wherever possible (where actions are taken only with a certain probability to avoid oscillatory behaviour), and for reasons of simplicity we have kept the frequency-adjustment and the phase-adjustment components of DPS scheme largely separate.

4.2.1 General Functionality

Before explaining phase-shifting and frequency-hopping in detail, we introduce some common elements used by both algorithms: A coordinator will use both its active and inactive periods to observe its current channel and other channels. The current channel is observed during the active period and in every other inactive period, the other channels are scanned in random order in the alternate inactive periods. The coordinator includes the number of distinct beacons counted on its current channel within a given time frame. Before scanning another channel, the coordinator stays in its own channel for the duration of a beacon period and detects as many other beacon packets as possible and include this information into each of its beacon packets in a new field called the *numberWBSNs* field. To estimate the number of WBSNs on its own current channel, the WBSN coordinator uses the maximum of its own beacon count and the *numberWBSNs* field from other beacons received on the current channel. When a coordinator listens to another channel to estimate the number of WBSNs there, it makes no attempt to count them by itself, but again extracts the *numberWBSNs* field from beacons observed there and uses the maximum such value as the current estimate of the number of WBSNs on the other channel.

Three states are identified in the DPS Scheme, namely: *Initial-unsettled*, *Unsettled* and *Settled* states. A WBSN initially starts its activity in initial-unsettled state and remain there for the period of 50 beacon intervals. This period is required for a WBSN to measure the packet loss rate and to determine whether it is below a given satisfaction threshold (satisfied) or above that (unsatisfied). The coordinator of a WBSN uses this information to transit to either settled or unsettled states, thereafter. More specifically, when the WBSN is satisfied, it will enter the settled state, in which it shows a reduced willingness to change its phase. In the unsettled state a WBSN is much more willing to adapt its phase, and when a settled and an unsettled WBSN clash with each other, the unsettled one is more likely to go to another phase.

As mentioned before, in this scheme , WBSNs are able to communicate with each other. Each coordinator constantly scans its channel for the duration of a BI to detect other beacon packets and include this information (observed number of other beacon packets) into the payload of its beacon packet and transmits it, routinely. Using this strategy, the coordinator of a WBSN always knows about the maximum number of detected WBSNs in its current channel.

Two important terms are used in the DPS Scheme: *adaptation-Period* and *jumping Probability*.

In the settled or unsettled state the WBSN sub-divides time into so-called *adaptation periods*, which consist of an integer number of beacon periods (we used **two** beacon periods in our simulations). The WBSN will update its packet loss rate observations and satisfaction during the adaptation period and any decision to change phase will only be triggered at the end of such a period. After each adaptation-period, if the packet loss rate had exceeded above the threshold, the coordinator of a WBSN informs the attached sensors about the new jumping point by including the new jumping point into the payload of the beacon packets in two consecutive superframes. The jumping point is determined randomly (uniform distribution). More specifically, when the coordinator of a WBSN decides to jump to a new phase, it randomly (uniform distribution) selects a real number from (0, length of a beacon period) and passes this information to its attached sensors using **two** consecutive beacon packets. Another term used in this scheme is the *jumping probability*. Each time that a WBSN calculates the packet loss rate, it updates its jumping probability. Basically, jumping to a new phase directly depends on the jumping probability which is a value between 0 and 1. If the jumping probability of a WBSN was above the threshold of 0.5, as soon as the adaptation period is over, the coordinator informs its attached sensors about the new phase (new jumping point) and the WBSN jumps to the new phase, thereafter. The usage of jumping probability is explained in detail according to the behaviour of a WBSN in each of the settled and unsettled states. The precise behaviour of a WBSN in each of the three states is as follows:

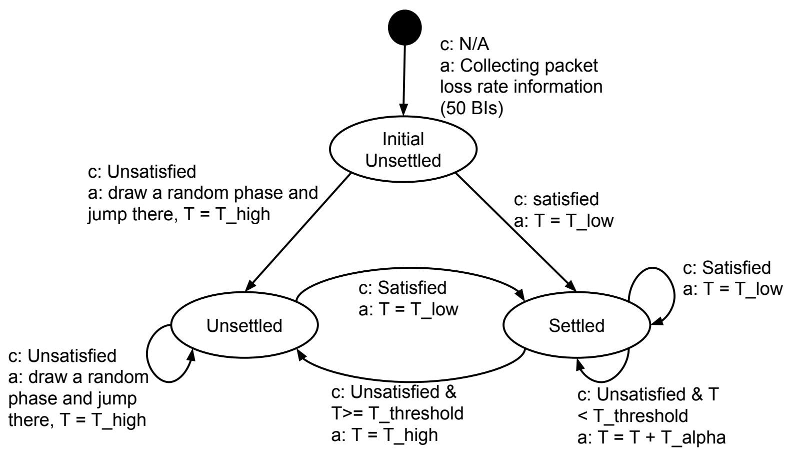


Figure 4.7: State machine diagram of the DPS Scheme

- **Initial-unsettled state:** A WBSN starts its activities from initial-unsettled state. In this state, the coordinator of a WBSN collects the satisfaction information over a certain time frame (50 beacon periods in this thesis) to determine the packet loss rate, its satisfaction status and from this the next state.

- **Unsettled state:** After the initial-unsettled state, if a WBSN was unsatisfied, it changes its state to the unsettled state and jumps to a new random phase as described earlier. In this state the jumping probability T is set to the highest value $T := T_{high}$ which is a parameter of the scheme and in this thesis has been set to T_{high}.With this, an unsatisfied WBSN will jump with high probability after the next adaptation period if it remains unsatisfied. This phase-jumping occurs repeatedly until a WBSN becomes satisfied. A satisfied WBSN in the unsettled state transits to the settled state and sets the jumping probability to the lowest value $T := T_{low}$, which again is a parameter of the scheme and for this thesis is set to T_{low}.

- **Settled state:** A WBSN in the settled state can be either satisfied or unsatisfied. When a WBSN is in the settled state and considers itself satisfied at the end of an adaptation period, it sets its jumping probability again to the lowest value, i.e. $T := T_{low}$. When the WBSN is unsatisfied, it increases its jumping probability by $T := min\{T + T_\alpha, T_{threshold}\}$ after the adaptation period, where T_α is another parameter, and $T_{threshold}$ bounds this growth. When $T_{threshold}$ is reached, the WBSN changes to the unsettled state and follows the activities mentioned for the unsatisfied node in the unsettled state.

Figure 4.7 represents the state machine diagram of the DPS Scheme, where T,T_{low}, T_{high}, $T_{threshold}$ and T_α are explained previously.

4.2.2 Frequency Adaptation

The coordinator of a WBSN initially generates a *random order* to scan the other channels. Each time the coordinator scans a new channel for a duration of the inactive period, it then returns to its original channel and scans it for a full beacon period to determine if any update is required (e.g. changing in the number of occupants). When a coordinator scans a new channel, it actually listens to the channel to receive any other beacon packets and extracts the detected number of occupants being included in them. Then the largest number of occupants extracted from the received beacon packets is considered as the number of occupants in that channel. Once a channel with the smallest number of occupants (with the difference of at least two WBSNs) is identified, the coordinator draws a random number from (0,1) as a hopping probability. If the hopping probability was above the threshold of 0.5, the coordinator informs its attached sensors in two consecutive superframes (after adaptation period) and switch to the new channel, thereafter. Otherwise, it stays on the same channel and keeps scanning the frequencies. Such channel hopping strategy (using the hopping probability) used not only for its simplicity in terms of design and implementation but also it is fairly similar[3] to the channel switching strategy described for dynamic passive schemes. The Scanning procedure of other operating frequencies is a procedure that occurs repeatedly throughout, and switching to the channel with the smallest number of occupants occurs regardless of the current channel quality. The WBSN that has switched to the new operating frequency reset its current state to initial-unsettled state and start collecting the satisfaction information.

4.2.3 DPS Scheme Limitation

Each time that a settled WBSN experiences the success rate below the satisfaction threshold, it increases its jumping probability ($T := min\{T + T_{\alpha}, T_{threshold}\}$) and it will move only when its jumping probability exceeds the $T_{threshold}$. However, an unsettled WBSN continuously shifts its beacon until a time slot / phase is found and the success rate goes above the satisfaction threshold. This implies that a subset of WBSNs will become settled relatively early and enjoy higher success rate (above the satisfaction threshold), while others become unsettled and shift their active phase comparatively more frequently. This will create a "fairness" issue, when the unsettled node shifts its beacon to another randomly selected time slot more frequently compared to the settled node. Covering this limitation is one of our suggestions for the future works.

[3]except for the usage of the hopping probability and also the scanning its own channel after scanning any other channel.

5 Sensitivity Analysis

The main objectives of the sensitivity analysis section are to explore the sensitivity of satisfaction rate against the variation of the k factors, and to identify those factors with the strongest impact on the responses. The Response Surface Methodology (RSM) is a well-known strategy, utilised in this thesis to determine the effect of k explanatory variables (factors) on one or more response variable(s) [86], [116],[113], [45]. Generally, in RSM, aims to develop a functional relationship between the response variable y, and a number of associated factors/explanatory variables $(x_1, x_2, x_3, ..., x_k,)$. The unknown relationship is approximated by a low-degree polynomial model:

$$Y = \alpha_0 + \sum_{i=1}^{k} \alpha_i \cdot x_i + \sum_{i=1}^{k} \sum_{j<i} \alpha_{i,j} \cdot x_i \cdot x_j + \epsilon \tag{5.1}$$

where ϵ represents the observed noise or error in the response y and $f(x_1, x_2, ..., x_k)$ represents the *response surface*. In this thesis, we have adopted an approach where each factor is assigned two different values: a minimum and a maximum value. These values are sensibly selected. This means that in a scenario with k independent variables (factors), a total of 2^k responses (for the dependent variable) should be produced using either simulation or experimentation studies. Therefore, this approach is also called a 2^k factorial design. Since each simulation run deals with random numbers and thus produces random output, at least 32 simulation replications are carried out for each parameter combination defined from the total of 2^k different parameter combinations. The average of these 32 simulation replications is used as the response value for that particular parameter combination and because of that we neglect the term ϵ. The simulation time is set to be long enough for each sensor node to generate 10,000 data packets (assuming it is always associated to its coordinator). At the end of each simulation replication, the satisfaction rate is calculated. Please note that 32 simulation replications were sufficient to reach a relative confidence interval half-width of 5% at a confidence level of 95% for the success rate. Finally, the best fit model (regression model) is obtained indicating the relationship between the independent variables and the observed (average) responses. This model is then utilised for further analysis of the relative impact of the considered factors.

5.1 Factors

The following factors are selected for our study:

- **Beacon order (x_1)**: as previously discussed, the beacon order (BO) parameter is used to calculate the beacon period and thus the beacon transmission rate. The minimum and maximum values for this parameter is defined as four and seven, respectively.

- **Superframe order (x_2)**: this parameter determines the active period within which the sensor device is allowed to transmit the collected data packet(s) to the coordinator. The minimum and maximum values for this parameter are one and three, respectively. Using this parameter setting, each superframe order can be combined with each of the beacon orders while still satisfying the constraint $SO \leq BO$.

- **MacMinBE (x_3) and macMaxBE (x_4)**: these parameters are internal parameters of the CSMA/CA MAC protocol. As previously mentioned, sensor devices must compete with each other to gain access to the medium. Therefore, they use the CSMA/CA mechanism to gain access to the medium while trying to avoid collisions. Carrier-sensing is used to check that the medium is not currently utilised by other nodes. However, before attempting to perform carrier-sensing, the MAC layer waits for a random back-off time. This random back-off time is drawn from the interval $[0, 2^{BE} - 1]$ using a uniform distribution. The BE is the backoff exponent which concludes how many backoff periods a sensor device should wait (on average) before attempting to assess the channel. The macMinBE is the initial value of BE and is increased each time the channel is sensed busy until the macMaxBE is reached.

- **System load or packet inter-arrival time (x_5)**: we assume that sensors generate packets periodically with a configurable packet inter-arrival time. Please note that in general the inter-arrival time and the beacon period / beacon order are not completely independent of each other, as the beacon period must be smaller than the inter-arrival time for the latter to be meaningful. Therefore we have chosen the minimum inter-arrival time to be larger than the largest beacon period.

We argue that these factors include the most relevant MAC factors: as they determine the overall channel load generated by one WBSN and the âĂIJaggressivenessâĂİ of channel access. For all other parameters we use the default values suggested by the standard. We have also assessed the impact of some of the other parameters in preliminary studies. For example, for the number of MAC retransmissions we found that there are only minor performance differences for three or more retransmissions. It was imperative to keep the number of factors limited, as otherwise simulation times would have become prohibitive. The RSM approach (described in Section 5.2) will allow us to obtain quantitative insight into the relative impact of these factors using only two different levels for each of them, saving many experiments as compared to a full factorial design.

Table 5.1 represents the minimum and maximum values for the considered MAC parameters.

Parameter	**Factor variable**	**Min value (-1)**	**Max value (1)**
MAC Layer (CC2420) Parameters			
Beacon Order	x_1	4	7
Superframe Order	x_2	1	3
macMinBE	x_3	1	macMaxBE
macMaxBE	x_4	3	8
Application Layer Parameters			
Packet Inter-arrival Time	x_5	5 s	10 s

Table 5.1: Factors, their RSM variables and their Min/Max values

5.2 Response Surface Methodology

In this section, the RSM approach and its main objectives are briefly explained. The RSM is a group of mathematical and statistical methods used for building an empirical model. In order to build such model, a series of simulation or experimentation tests (called runs) is carried out in which input variables (or factors) are changed in order to identify the reasons for probable changes in the output response [45].

Presume there is a response variable $y \in \mathcal{R}$ where n is the number of observations, assumed to be affected by a vector of independent variables $a \in \mathcal{R}$. k is the number of independent variables. The relationship between the dependent and independent variables could be demonstrated as:

$$y = f(a_1, a_2, ..., a_k) + \epsilon \tag{5.2}$$

where $f()$ is the function of the system that associates response variable (here: the satisfaction rate) to the independent variables $a_1, a_2, ..., a_k$ and ϵ represents the errors of the model. A popular for for $f()$ is a low order polynomial. In order to proceed to further response surface model analysis (i.e. regression), the independent variables (or design parameters) are expressed in their physical units, must be converted to a dimensionless quantities with the zero mean and the same standard deviation i.e. the response variable is expressed as:

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum \sum_{i<j} \beta_{ij} x_i x_j \tag{5.3}$$

where x_i and x_j are the design parameters in their coded format, and $\beta_0, \beta_i, \beta_{ii}, \beta_{ij}$ are the coefficient of the intercept, linear, quadratic and the interaction in the regression model, respectively. The coefficients of polynomial represented in equation 5.3 are determined through n simulation runs.

For each parameter setting $(x_1, \ldots, x_k) \in \{-1, 1\}^k$ we obtain a response value $y_{x_1,\ldots,x_k}$. Observing that the regression model (Equation 5.3) is linear in the parameters β_x and we can represent all parameters as a vector:

$$\beta = (\beta_0, \beta_1, \ldots, \beta_k, \beta_{2,1}, \beta_{3,1}, \beta_{3,2}, \beta_{4,1}, \ldots, \beta_{k,k-1}) \tag{5.4}$$

and the responses as a vector

$$y = (y_{(-1,\ldots,-1)}, y_{(-1,\ldots,-1,1)}, \ldots, y_{(1,\ldots,1)}) \tag{5.5}$$

and then set up the linear equation system

$$y = S \cdot \beta \tag{5.6}$$

where S is the so-called sign matrix, in which the row corresponding to response $y_{x_1,\ldots,x_k}$ with $(x_i \in \{-1, 1\})$ is formed as $(1, x_1, \ldots, x_k, x_2 \cdot x_1, x_3 \cdot x_2, x_3 \cdot x_1, \ldots, x_k \cdot x_{k-1})$. Each matrix entry thus is either '1' or '-1'. The columns of matrix S are orthogonal. However, note that S has 2^k rows and only $1 + \frac{k(k+1)}{2}$ columns, so this linear system of equations is over-determined and we compute the least-squares solution for it.[1] The intercept β_0 is the mean value of all observed responses, i.e.

$$\beta_0 = \bar{y} = \frac{1}{2^k} \sum_{x \in \{-1,1\}^k} y_x \tag{5.7}$$

and we use this to calculate the so-called *sum-of-squares-total* (SST)

$$SST = \sum_{x \in \{-1,1\}^k} (y_x - \bar{y})^2 \tag{5.8}$$

which represents the total amount of variation observed in the experiments. After elementary algebra and exploiting orthogonality of the columns of S one gets that

$$SST = 2^k(\beta_1^2 + \ldots + \beta_k^2 + \beta_{2,1}^2 + \ldots + \beta_{k,k-1}^2) \tag{5.9}$$

so that the relative impact of factor k or any interaction k, j can be expressed as:

$$\frac{2^k \beta_k^2}{SST} \quad , \quad \frac{2^k \beta_{k,j}^2}{SST} \tag{5.10}$$

which represents the contribution of each factor in the total observed variation.

On the other hand, the *sum-of-squares-errors* is a measure for the total error introduced through the regression, it is given as:

$$SSE = \sum_{x \in \{-1,1\}^k} \left(y_x - \left(\beta_0 + \sum_{i=1}^{k} \beta_i \cdot x_i + \sum_{i=1}^{k} \sum_{j<i} \beta_{i,j} \cdot x_i \cdot x_j \right) \right)^2 \tag{5.11}$$

The quality of the regression model (and here: how harmful it is to discard higher-order interactions) can be expressed as the coefficient of determination (also called the R^2 value), given by:

$$R^2 = \frac{SST - SSE}{SST} \tag{5.12}$$

[1] One could make S quadratic, and then in fact completely orthogonal, by expanding Equation 5.3 to include terms for the higher interactions of three, four, ..., k factors.

where higher values are better.

5.3 Simulation Approach

To obtain the results we have used the Castalia open-source network simulator in version 3.2, which is designed for WBSNs simulation scenarios [16], and have extended it to implement the schemes described in Section 4. The main parameters of the MAC and the packet inter-arrival times have been chosen as described in Tables 3.1 and 5.1. For the wireless channel we use the log-distance model [98]. Since the WBSNs were all placed in the same location and do not move (as described in Section 3.3) we have eliminated packet losses resulting from path loss, fading, shadowing or hidden-terminal situations, and all packet losses observed are due to direct collisions.

For each possible factor combination $c = c_{x_1,\ldots,x_5}, x_i \in \{-1, 1\}$ (i.e. each possible allocation of 1 and -1 to the five factors x_1 to x_5) and each investigated scheme we have run a number of at least 64 independent replications. Each replication lasted 10,000 or 20,000 simulated seconds, so that on average each sensor node generates 2,000 packets, depending on the chosen inter-arrival time. Further replications were added when needed to achieve a relative half-width of the confidence interval not larger than 5%, at a 95% confidence level, for the success rate. From the success rates we have then determined the satisfaction rates for each replication. The satisfaction rates of all replications for one parameter allocation / scheme have then been averaged to obtain the response y_c value being used in the RSM analysis.

6 Simulation-based Performance Evaluation of Passive Schemes

In this chapter the performance of the proposed schemes in our simulation study, is evaluated and discussed. As a reminder, the performance metrics are briefly explained in Section 6.1. Thereafter, the performance of the passive schemes is discussed and evaluated in detail in Section 6.2. The sensitivity of the system parameters and their contributions on the satisfaction rate is elaborated in Section 6.3. The Chapter is continued with Sections 7.1 and 7.2 where provide comparisons between the proposed active and passive schemes in two different environments (static and dynamic environments). The sensitivity analysis of the proposed active scheme is then discussed in Section 7.3 and finally, the summary of this chapter is given in section 7.5. This contents of this chapter are published in [81], [77], [76], [82] and [83].

In this thesis, the Castalia network simulator was used to simulate the network scenarios and to extract the necessary results. In our simulation scenarios, 16 channels are available to be utilised by WBSNs, external interference is not considered. To show the impact of internal interference on the WBSN performance, the number of WBSNs is varied using the set $\Delta = \{50, 100, 150, 200, 250\}$. For each $\delta \in \Delta$, the WBSNs are initially distributed (uniform distribution) over 16 available operating frequencies. For each scheme in this Chapter, at least 64 replications are carried out and Further replications were added when needed to achieve a relative half-width of the confidence interval not larger than 5%, at a 95% confidence level, for the success rate. From the success rates we have then determined the satisfaction rates for each replication. The average of satisfaction rates of all replications for each scheme is then represents the satisfaction rate as one of our main performance measures.

6.1 Performance Metrics

This Section briefly explains the considered performance metrics in this thesis as a reminder. Two types of performance measures are considered in this thesis, namely: primary and secondary performance measures. The primary performance measures are the satisfaction rate and the channel capacity. the secondary performance measures are energy consumption, orphan period.

- *Satisfaction rate* is defined as the percentage of satisfied[1] WBSNs out of the given total number of WBSNs.

- *Channel capacity* is defined as the number of WBSNs that, for the given scheme, can be located at the same spot in such a way that at least 95% of them are satisfied.

- *Success rate* is the average of successfully transmitted of all uplink data packets sent by four (equally loaded) sensor devices and the overall average success rate over all replication is the average of success rates of all WBSNs. The success rate and satisfaction rate performance measures are both geared towards the applications that have some notion of acceptable and unacceptable performance e.g. in terms of packet losses for regularly transmitted sensor signals. While briefly show some results regarding the success rate in Section 6.3, we mainly focus on the satisfaction rate in other Sections. This decision

[1] A WBSN is regarded as satisfied if the average successful transmission of the data packet is 95% or more.

is made due to considering the criticality of medical applications in which the performance of WBSNs is supposed to be ”acceptable“ and as high as possible.

- *Energy consumption* is the amount of energy consumed by a node transceivers in each state (sleep, transmit, listen).

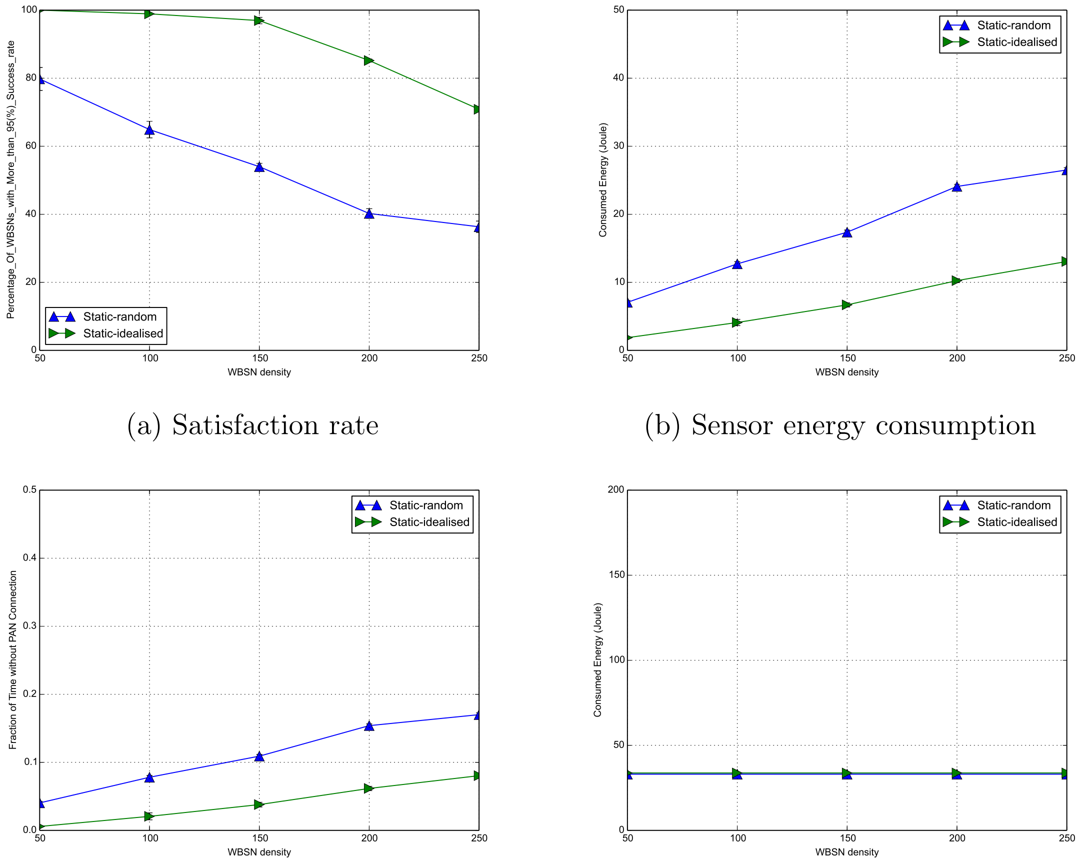
- *Orphan period* is defined as the total duration of time that the sensor device has spent without being associated to the PAN coordinator.

6.2 Performance Evaluation of Passive Schemes: Static Environment

The performance evaluation of the passive schemes is discussed in detail in this section. Firstly, a hypothetical upper band and a lower band of the achievable performance are illustrated and the gap between them is displayed. Thereafter, it is shown that how selecting an operating frequency with the smallest number of occupants along with the capability of channel switching can actually improve the performance and narrow the gap between the hypothetical upper and lower band of the achievable performance. Please note that in this section, the parameters are set with the values shown in Table 3.1.

6.2.1 Hypothetical upper and lower bands

As a reminder, the static-random scheme is the one in which a WBSN autonomously and randomly (using uniform distribution) picks an operating frequency at the initial stage of its activation. As mentioned previously, no measurement is performed in this scheme, the phase / time alot is chosen randomly, no adaptation is occurred and a WBSN stays in its initially-selected channel throughout. However, in the static-idealized scheme, the phase and the operating frequency of WBSNs are determined at the initialisation time. More precisely, WBSNs are (nearly) evenly distributed over 16 available operating frequencies and on each operating frequency, the WBSNs are equidistantly spread over time. Therefore, in this thesis, the static-random and the static-idealized are considered as the hypothetical lower and upper bands of the achievable gains, respectively. The performance of these two schemes is shown in Figure 6.1.



(a) Satisfaction rate

(b) Sensor energy consumption

(c) Orphan period

(d) Coordinator energy consumption

Figure 6.1: The performance evaluation of the proposed hypothetical upper and lower bands.

The gap between the satisfaction rates of both schemes (displayed in Figure 6.1a) highlights the need for improving the performance of IEEE 802.15.4 MAC protocol in order to mitigate the destructive impacts of the internal interference. Although the satisfaction rate of both schemes shows a downward trend as the total number of WBSNs increases, the static-idealized scheme has by far outperformed the static-random scheme in terms of both primary and secondary performance measures, except for the coordinator energy consumption (the same amount of energy is consumed by coordinators in both schemes). Figure 6.1c represents the average fraction of time that the sensor devices spent in the orphan state. Clearly, the (nearly) even distribution of WBSNs over 16 available channels along with equidistant spreading them over time in each channel (as in static-idealized) has resulted in experiencing *lower* active period overlapping ratio in comparison with simply distributing (using uniform distribution) them over 16 available channels (as in static-random). As a result, sensor devices in static-idealized scheme consumed *less* energy compared to the static-random scheme. Figures 6.1c and 6.1b show the orphan period and sensor energy consumption, respectively. Since the coordinator of a WBSN does not perform any extra activity (e.g. frequency spectrum scanning) in the static-idealized and the static-random schemes, the coordinator energy consumption of both schemes are the same. Figure 6.1d shows the coordinator energy consumption of both schemes.

6.2.2 Frequency Adaptation

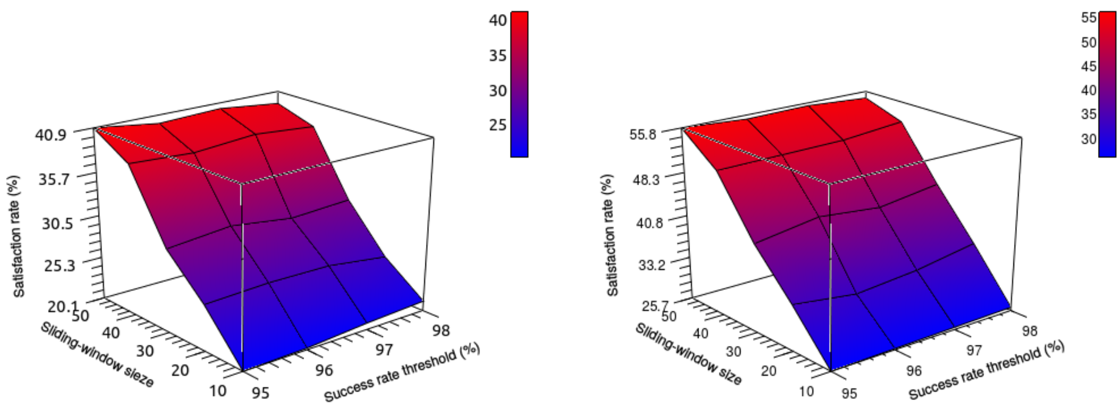
Three passive adaptive-frequency schemes are investigated in this thesis, namely: dynamic-random-hopping, dynamic-targeted-hopping with continuous assessment and dynamic-targeted-hopping with periodic assessment. In the dynamic-random-hopping scheme, the coordinator of a WBSN continuously (using a number of beacon periods in a sliding-window fashion) assesses the quality of the channel. If the packet loss rate has exceeded the given threshold, it picks a new channel randomly (using the uniform distribution and considering all channels except for the current one) and the whole WBSN jumps there. In the dynamic-targeted-hopping scheme with continuous assessment scheme, the coordinator of a WBSN not only continuously assesses the quality of the current channel but also it continuously scans other channels during its inactive time (one channel per beacon period) in order to find the channel with the smallest number of occupants. Once the packet loss rate has exceeded the given threshold, the WBSN jumps to the channel with the smallest number of occupants. However, in dynamic-targeted-hopping with periodic assessment, the coordinator of a WBSN periodically (every 50 beacon periods) assesses the quality of the current channel. In this scheme if the packet loss rate has exceeded the pre-defined threshold, the coordinator starts scanning the whole frequency spectrum (one channel per beacon period) in order to find the channel with the smallest number of occupants. Clearly, there are two factors that could play key roles on the overall performance of WBSNs, namely: the given threshold – in order to see if the packet loss rate has exceeded the given threshold – and the size of the sliding-window. Therefore, a simulation study is conducted to obtain the suitable values for the mentioned factors that could result in highest performance gain for both dynamic-random-hopping and dynamic-targeted-hopping with continuous assessment.

Since one of the objectives of this thesis is increasing the number of WBSNs in the presence of internal interference, the energy consumption of the coordinators is of lesser importance and therefore, the employment of dynamic-targeted-hopping with continuous assessment is strongly recommended in comparison to dynamic-targeted-hopping with periodic assessment. This is mainly because in dynamic-targeted-hopping with continuous assessment, the coordinator of a WBSN has the opportunity of changing the operating frequency at the exact moment that the packet loss exceeds above the threshold. However, in dynamic-targeted-hopping, due to the periodic assessment of channel quality, a WBSN is required to wait for 50 beacon periods and then jumps to another channel (if required). Figure 6.3 shows the satisfaction rate and the coordinator energy consumption diagrams of the both dynamic-targeted-hopping schemes. In both dynamic-targeted hopping with continuous assessment and dynamic-random-hopping schemes two key parameters are used, namely: sliding window and success rate threshold (or conversely packet loss rate threshold). Thus, a simulation study is conducted to choose values for these parameters that result in the highest performance gain for WBSNs. Table 6.1 shows the mentioned parameters and the variation of their values.

Table 6.1: Value variation

Parameter	values	step
sliding-window size	10 to 50 BIs	10 BIs
success rate threshold	95% to 98%	1%

Figure 6.2 shows the achieved satisfaction rate for dynamic-targeted-hopping and dynamic-random-hopping schemes when $\delta = 250WBSNs$.



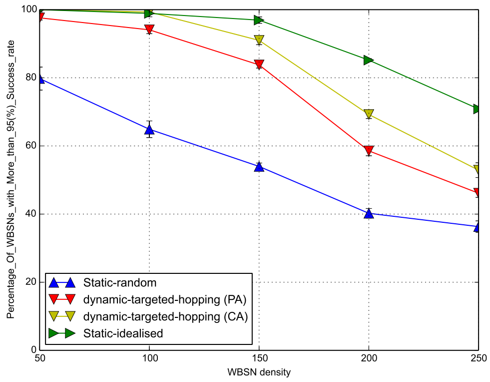
(a) dynamic-random-hopping

(b) dynamic-targeted-hopping

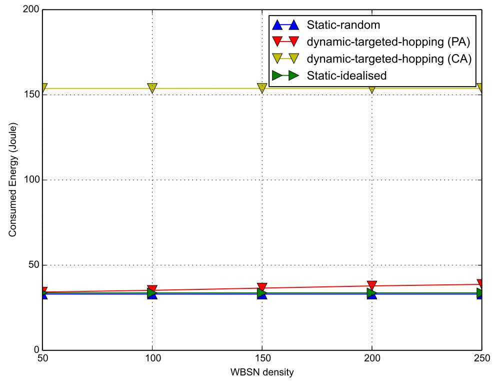
Figure 6.2: The performance evaluation of the dynamic-targeted-hopping and dynamic-random-hopping when sliding-window size and success rate threshold are varied for WBSNs = 250.

Clearly, the highest satisfaction rate is obtained when the size of sliding-window is 50 BIs and the success rate threshold is 95%[2]. This is mainly due to sliding-window size = 50 BIs provides a better estimation of the channel quality – because of assessing more packet loss information – compared to sliding-window size = 10 BIs. Therefore, this particular parameter configuration is used for both of the above-mentioned schemes.

[2]For the same sliding-window size, the differences between different success rate thresholds are insignificant. However, success rate threshold = 95%, on average, achieves the highest satisfaction rate

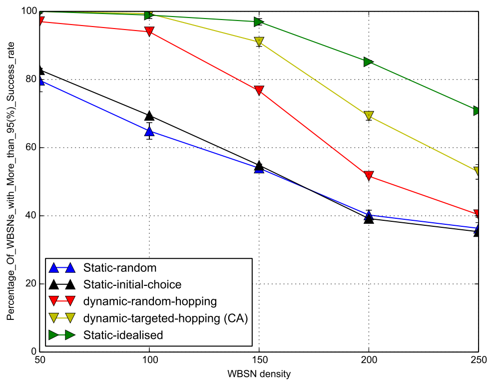


(a) Satisfaction rate

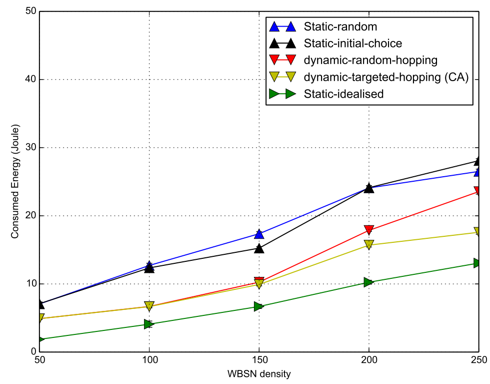


(b) Coordinator energy consumption

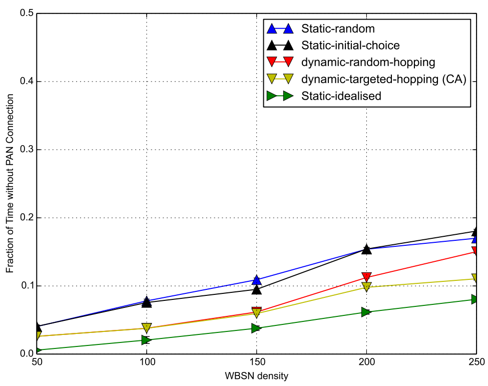
Figure 6.3: The performance evaluation of the dynamic-targeted-hopping schemes with the continuous assessment (CA) and the periodic assessment (PA).



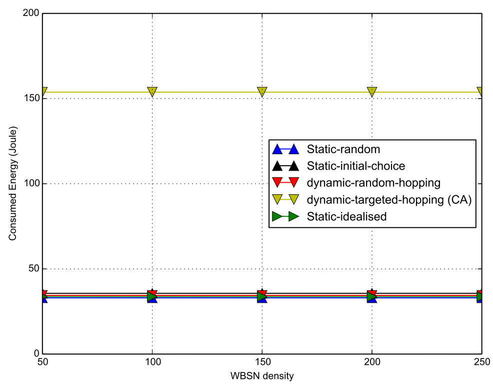
(a) Satisfaction rate



(b) Sensor energy consumption



(c) Orphan period



(d) Coordinator energy consumption

Figure 6.4: The performance evaluation of the proposed passive schemes in Static Environment

Figure 6.4 shows the performance of all passive schemes. The presented results highlight a number of interesting points regarding the satisfaction rate:

- The static-idealized scheme outperforms the other passive schemes in all aspects. In this scheme, WBSNs are evenly distributed over both frequency and time / phase, whereas the second best scheme (dynamic-targeted-hopping with continuous assessment) only achieves an equal distribution of WBSNs over 16 available frequencies but do not change the phase. More specifically, when dynamic-targeted-hopping scheme is employed in static environment, WBSNs do not change any phases and stick to the initial random distribution of phases. However, adaptive frequency hopping – when two conditions are met: packet loss rate exceeds the given threshold, and there is a channel with smaller number of occupants with the difference of at least two WBSNs – eventually achieves almost even distribution of WBSNs over 16 available channels but WBSNs stick to their initial phases throughout. Therefore, the performance difference between static-idealized and the dynamic-targeted-hopping scheme can be explained by the lack of phase adjustment. Moreover, although the size of the performance gap has become substantially smaller, there is still a considerable gap between dynamic-targeted-hopping scheme and the static-idealized scheme which indicates the advantage of the phase adjustment.

- The differences between the dynamic-targeted-hopping with continuous assessment scheme and the one with periodic assessment are the period of assessing the quality of the current channel and the spectrum scanning procedure (continuous or non-continuous manner). In dynamic-targeted-hopping with continuous assessment scheme, the channel quality assessment and the spectrum scanning procedure are two separate procedures that are performed continuously per beacon period. However, in the dynamic-targeted-hopping with periodic assessment, the spectrum scanning is a follow-up procedure that will be performed only if the packet loss rate (as a result of periodic assessment of the channel quality) exceeds the given threshold. Thus the performance difference between these two schemes can be mostly attributed to changing the operating frequency at the exact moment that the packet loss has exceeded the threshold of 5%.

- The difference between the dynamic-random-hopping scheme and the dynamic-targeted-hopping scheme is the random selection of a new operating frequency when the packet loss rate has exceeded the threshold of 5%. Therefore, the performance difference between these schemes can be attributed to switching to the channel will the smallest number of occupants (as a result of the spectrum scanning procedure) in the dynamic-targeted-hopping scheme. Although the dynamic-random-hopping scheme shows modest performance differences to the dynamic-targeted-hopping scheme, it still substantially outperforms both static-initial-choice and the static-random schemes. This suggests that higher satisfaction rate is obtainable as a result of frequency hopping.

- In the static-initial-choice scheme the coordinator of a WBSN scans the whole frequency spectrum in order to find a operating frequency with the smallest number of occupants and stays in that operating frequency throughout. The frequency spectrum scanning procedure is performed at the time of WBSN activation and in a random order. This strategy, has slightly improved the satisfaction rate when the total number of WBSNs is smaller than approximately 150 WBSNs. However, as the number of WBSNs increases, a sensor device is more likely unable to find the beacon packets being transmitted by its coordinator at initialisation time. As a result, the satisfaction rate of the static-initial-choice scheme has slightly dropped below the satisfaction rate of the static-random scheme when the total number of WBSNs is larger than 150.

Orphaning duration (the period of time that a sensor device is not associated the PAN coordinator) also plays a key role on the amount of energy consumed by the sensor devices. An orphan sensor device has to scan the current channel (for the schemes with no adaptation) or the whole frequency spectrum (for the schemes with frequency adaptation enabled) to find its coordinator. This scanning is a very energy consuming task which is originally caused by the loosing four consecutive beacon packets and transitioning to the orphan state. The results regarding the energy consumption of the sensor devices, their orphan period and the coordinator energy consumption are shown in Figures 6.4b, 6.4c and 6.4d, respectively. The presented results highlight a number of interesting points:

- Clearly, an even distribution of WBSNs over available operating frequencies and phases (static-idealized scheme) causes a lower overlapping ratio of active periods. As a result, the probability of packet collisions is decreased and lesser beacon packets are lost. Thus, a sensor device stays connected / synchronised to its associated coordinator for a longer period (or conversely has a shorter orphan period). Therefore, a sensor device consumes less energy to scan the channel in order to re-associate with the its coordinator.

- Frequency adaptation, however, has caused a sensor device to become orphan more often. In the proposed (passive) frequency adaptive schemes WBSNs are just capable of switching to other channel and they do not change their phases. Thus, as the number of WBSNs increases in the channel, the active periods would still highly likely overlap on each other and consequently, a higher packet collision rate is expected to happen compared to the static-idealized scheme. Considering the orphan period diagram, the gap between the static-idealized scheme and the dynamic-targeted-hopping scheme can again be explained by the lack of phase adjustment. As a result, the sensor energy consumption in the dynamic-targeted-hopping scheme is comparatively larger than the consumed energy by sensor devices in static-idealized scheme.

- The gap between the dynamic-random-hopping scheme and the dynamic-targeted-hopping scheme can be attributed to the only difference between these two schemes which is the way that the new channel is determined. In dynamic-random-hopping scheme, the new channel is selected randomly, while in the dynamic-targeted-hopping scheme the channel with the smallest number of occupants is selected as the new channel to hop on. The new-channel-selection strategy in the dynamic-targeted-hopping scheme would eventually result in a better distribution of WBSNs over all available channels. As the number of WBSNs increases, this strategy becomes more effective and the gap becomes more highlighted.

- There is still a considerable gap between the dynamic-random-hopping scheme and the static-random scheme which highlights the advantage of a frequency adaptation strategy in terms of both orphan period and the energy consumption of the sensor devices.

- Considering the orphan period diagram related to the static-initial-choice scheme, since coordinators scan the whole spectrum frequency at the initialisation time in order to find the channel with the smallest number occupants, sensor devices become orphan at the initialisation time. Therefore, orphan sensor device initially has to scan the whole frequency spectrum to find its associated coordinator. Additionally, as the number of WBSNs increases in the channel, it becomes difficult for the orphan sensor device to find the beacon packet sent by its coordinator due to higher probability of beacon packet collisions (colliding with each other or with data packets). As a result, the static-initial-choice scheme shows longer orphan periods compared to the static-random scheme as the number of WBSNs exceeds above 200.

6.3 Passive Schemes And the Sensitivity Analysis of System Parameters

In the previous section, it is observed that an even distribution of WBSNs over the available operating frequencies along with equidistant spreading them in time in each channel results in the highest satisfaction rate. Furthermore, the frequency-hopping strategy could substantially increase the satisfaction rate. In this section the performance of the above-mentioned passive schemes is explored using different parameter configurations. More specifically, the sensitivity of the satisfaction rate against variations of several important system parameters (i.e. beacon order, super-frame order, macMinBE, macMaxBE and packet inter-arrival time) is investigated. This study has a number of important results: 1) to be guided on how to choose / adapt system parameters in order to result in higher satisfaction rate. 2) to explore and compare the behaviour of the considered schemes in order to make sure that the difference in their obtained results can be extended for a range of varying system parameter configurations. 3) to identify the parameters that contribute the most to the observed variation. To accomplish this, the *response surface methodology* is employed. The value-variation of the above-mentioned system parameters is shown in Table 5.1. Firstly, the results for the satisfaction rate (as the response variable) are discussed in separate table followed by the fitted response models for each $\delta \in \Delta = \{50, 100, 150, 200, 250\}$. The results for the static-initial-choice scheme were generally very similar to the results for the static-random scheme and are not considered furthermore. For each $\delta \in \Delta$, a table is presented that includes the percentage contribution to variation of the linear and interaction coefficients (Table 6.2 to 6.6). After each table,four equations are presented that are the fitted response models (with coefficients trimmed to two decimals) for static-idealized, static-random, dynamic-random-hopping and dynamic-targeted-hopping schemes (Equations 6.1 to 6.20), respectively. Table 6.7 contains the intercept values (β_0) for the considered schemes and for each $\delta \in \Delta$,and then the percentage impact of the linear terms for each of the considered system parameters (variables: BO, SO, macMinBE, macMaxBE and system load) are plotted in Figure 6.5.

The followings are the interesting points highlighted by the obtained results:

- In all tables (for each $\delta \in \Delta$) the R values for all considered schemes indicate that the regression ansatz (given in Equation 5.1) covers almost all the observed variations. This shows that our presented incomplete model (in which all interactions between three or more factors are ignored) is in fact a good approximation.

- The static-idealized and dynamic-targeted-hopping schemes are, respectively, the best and second best schemes due to achieving the highest average satisfaction rate β_0 for each $\delta \in \Delta$. Considering Figure 6.5, it can be seen that for these two schemes the linear terms alone have already explained more than 80% of the observed variations[3]. Furthermore, for each considered scheme and for each $\delta \in \Delta$, the factor x_3 (*macMinBE*) is by far the most influential factor for the satisfaction rate. Considering the case $\delta = 250$, the impact of factor x_4 (*macMaxBE*) on the satisfaction rate becomes more noticeable, whereas the impact of other factors is comparatively negligible. The remaining variation (which is not covered by the linear terms) is mostly explained by the interaction of x_3 and x_4 ($x_3 x_4$ interaction terms). These obtained results suggest that for all considered schemes the factors x_3 (*macMinBE*) and x_4 (*macMaxBE*) have the most impact on the satisfaction rate (with macMinBE being the much more important one) and the adaptation or at least careful configuration of these parameters can be propounded as the potential for improvements.

- Again, by comparing the intercept values of all considered schemes (see Table 6.7) it can be observed that the static-idealized scheme, in which WBSN are

[3]For $\delta \in \Delta$ and $\delta < 250$ the linear terms explain more than 90%.

evenly distributed in both frequency and time / phase, is the overall best scheme. The dynamic-targeted-hopping scheme (in which WBSNs eventually achieve an equal distribution over available channels but stick to their initial random distribution of phases) is, however, the second best scheme in terms of the average satisfaction rate (β_0) for each $\delta \in \Delta$. This again suggests that the performance difference between static-idealized and the dynamic-targeted-hopping schemes (for the same range of parameter variations) can be explained by the lack of phase adjustment in the dynamic-targeted-hopping scheme.

- Following the line of reasoning given before for the performance difference between the dynamic-random-hopping and the static-random schemes (the advantage of frequency adaptation), the performance difference between these schemes is now more highlighted for a range of parameter variations: again judging from the intercept values, it can be observed that frequency adaptation offers substantial improvement in terms of satisfaction rate.

- Considering the static-random diagrams in Figure 6.5, the relative impact of the factors is more noticeable as the number of WBSNs is increased: the impact of the *macMinBE* becomes significantly smaller, whereas the factor x_1 (BO) becomes noticeably larger as the number of WBSNs is increased compared to other schemes.

	static-idealized	**static-random**	**dynamic-random**	**dynamic-targeted**
SST	55831.5	66509.5	63712.9	61494.0
SSE	1463.9	3368.0	801.1	1526.4
R^2	0.97	0.95	0.99	0.98
α_0	62.11	46.75	56.77	59.44
% contrib. x_1	2.35	1.3	1.09	1.91
% contrib. x_2	3.14	6.0e-2	1.12	2.08
% contrib. x_3	80.91	87.48	91.81	83.95
% contrib. x_4	1.58	1.66	0.49	1.44
% contrib. x_5	0.41	1.77	0.24	0.42
% contrib. x_1x_2	0.32	8.0e-2	0.21	0.27
% contrib. x_1x_3	2.12	0.16	1.02	1.73
% contrib. x_1x_4	4.0e-2	0.44	2.0e-2	0.11
% contrib. x_1x_5	0.0	0.55	1.0e-2	3.0e-2
% contrib. x_2x_3	2.88	0.13	0.98	1.83
% contrib. x_2x_4	0.74	4.0e-2	0.29	0.73
% contrib. x_2x_5	0.33	1.0e-2	0.23	0.5
% contrib. x_3x_4	1.4	0.68	0.39	1.27
% contrib. x_3x_5	0.36	0.42	0.22	0.38
% contrib. x_4x_5	2.0e-2	0.85	2.0e-2	7.0e-2

Table 6.2: Main RSM results for the satisfaction rates of all considered schemes for 50 WBSNs.

The fitted models for $\delta = 50$:

$$
\begin{aligned}
Y_{\text{static-idealized}} = \quad & && (6.1)\\
& 62.11 \\
& -6.40 \cdot x_1 - 7.41 \cdot x_2 + 37.57 \cdot x_3 + 5.25 \cdot x_4 + 2.68 \cdot x_5 \\
& +2.35 \cdot x_1x_2 + 6.09 \cdot x_1x_3 - 0.80 \cdot x_1x_4 + 0.06 \cdot x_1x_5 + 7.09 \cdot x_2x_3 \\
& -3.60 \cdot x_2x_4 - 2.40 \cdot x_2x_5 - 4.94 \cdot x_3x_4 - 2.51 \cdot x_3x_5 + 0.58 \cdot x_4x_5 \\
Y_{\text{static-random}} = \quad & && (6.2)\\
& 46.75 \\
& -5.19 \cdot x_1 - 1.11 \cdot x_2 + 42.64 \cdot x_3 + 5.87 \cdot x_4 + 6.07 \cdot x_5 \\
& +1.30 \cdot x_1x_2 - 1.83 \cdot x_1x_3 + 3.02 \cdot x_1x_4 + 3.39 \cdot x_1x_5 + 1.65 \cdot x_2x_3 \\
& -0.96 \cdot x_2x_4 - 0.34 \cdot x_2x_5 + 3.77 \cdot x_3x_4 + 2.95 \cdot x_3x_5 - 4.21 \cdot x_4x_5 \\
Y_{\text{dynamic-random}} = \quad & && (6.3)\\
& 56.77 \\
& -4.67 \cdot x_1 - 4.72 \cdot x_2 + 42.75 \cdot x_3 + 3.11 \cdot x_4 + 2.21 \cdot x_5 \\
& +2.07 \cdot x_1x_2 + 4.51 \cdot x_1x_3 - 0.55 \cdot x_1x_4 - 0.42 \cdot x_1x_5 + 4.41 \cdot x_2x_3 \\
& -2.42 \cdot x_2x_4 - 2.15 \cdot x_2x_5 - 2.80 \cdot x_3x_4 - 2.08 \cdot x_3x_5 + 0.55 \cdot x_4x_5 \\
Y_{\text{dynamic-targeted}} = \quad & && (6.4)\\
& 59.44 \\
& -6.05 \cdot x_1 - 6.33 \cdot x_2 + 40.16 \cdot x_3 + 5.26 \cdot x_4 + 2.85 \cdot x_5 \\
& +2.29 \cdot x_1x_2 + 5.77 \cdot x_1x_3 - 1.43 \cdot x_1x_4 - 0.75 \cdot x_1x_5 + 5.93 \cdot x_2x_3 \\
& -3.75 \cdot x_2x_4 - 3.11 \cdot x_2x_5 - 4.94 \cdot x_3x_4 - 2.72 \cdot x_3x_5 + 1.18 \cdot x_4x_5
\end{aligned}
$$

	static-idealized	**static-random**	**dynamic-random**	**dynamic-targeted**
SST	57814.6	58236.8	63001.2	62460.7
SSE	1532.5	2841.5	993.4	1681.6
R^2	0.97	0.95	0.98	0.97
α_0	61.01	41.26	54.57	58.71
% contrib. x_1	1.81	9.0e-2	0.68	1.98
% contrib. x_2	2.68	0.0	1.07	1.92
% contrib. x_3	82.84	84.18	92.38	84.09
% contrib. x_4	1.56	3.48	0.66	1.28
% contrib. x_5	0.38	2.61	0.5	0.44
% contrib. x_1x_2	0.27	5.0e-2	0.28	0.4
% contrib. x_1x_3	1.63	1.0e-2	0.82	1.66
% contrib. x_1x_4	5.0e-2	0.14	5.0e-2	0.13
% contrib. x_1x_5	0.0	0.66	6.0e-2	4.0e-2
% contrib. x_2x_3	2.45	9.0e-2	0.67	1.81
% contrib. x_2x_4	0.86	1.0e-2	0.26	0.7
% contrib. x_2x_5	0.34	1.0e-2	0.15	0.5
% contrib. x_3x_4	1.39	2.44	0.17	1.05
% contrib. x_3x_5	0.32	1.09	0.16	0.4
% contrib. x_4x_5	2.0e-2	1.48	1.0e-2	0.1

Table 6.3: Main RSM results for the satisfaction rates of all considered schemes for 100 WBSNs.

The fitted models for $\delta = 100$:

$$\begin{aligned}
&Y_{\text{static-idealized}} = \\
&\quad 61.01 \\
&\quad -5.72 \cdot x_1 - 6.96 \cdot x_2 + 38.69 \cdot x_3 + 5.32 \cdot x_4 + 2.61 \cdot x_5 \\
&\quad +2.22 \cdot x_1x_2 + 5.42 \cdot x_1x_3 - 0.93 \cdot x_1x_4 + 0.09 \cdot x_1x_5 + 6.65 \cdot x_2x_3 \\
&\quad -3.94 \cdot x_2x_4 - 2.48 \cdot x_2x_5 - 5.01 \cdot x_3x_4 - 2.42 \cdot x_3x_5 + 0.59 \cdot x_4x_5
\end{aligned} \tag{6.5}$$

$$\begin{aligned}
&Y_{\text{static-random}} = \\
&\quad 41.26 \\
&\quad -1.25 \cdot x_1 - 0.17 \cdot x_2 + 39.14 \cdot x_3 + 7.96 \cdot x_4 + 6.89 \cdot x_5 \\
&\quad +1.00 \cdot x_1x_2 + 0.35 \cdot x_1x_3 + 1.59 \cdot x_1x_4 + 3.46 \cdot x_1x_5 + 1.31 \cdot x_2x_3 \\
&\quad -0.33 \cdot x_2x_4 - 0.32 \cdot x_2x_5 + 6.67 \cdot x_3x_4 + 4.45 \cdot x_3x_5 - 5.20 \cdot x_4x_5
\end{aligned} \tag{6.6}$$

$$\begin{aligned}
&Y_{\text{dynamic-random}} = \\
&\quad 54.57 \\
&\quad -3.66 \cdot x_1 - 4.58 \cdot x_2 + 42.65 \cdot x_3 + 3.61 \cdot x_4 + 3.13 \cdot x_5 \\
&\quad +2.34 \cdot x_1x_2 + 4.02 \cdot x_1x_3 - 0.97 \cdot x_1x_4 - 1.10 \cdot x_1x_5 + 3.62 \cdot x_2x_3 \\
&\quad -2.25 \cdot x_2x_4 - 1.73 \cdot x_2x_5 - 1.83 \cdot x_3x_4 - 1.76 \cdot x_3x_5 + 0.53 \cdot x_4x_5
\end{aligned} \tag{6.7}$$

$$\begin{aligned}
&Y_{\text{dynamic-targeted}} = \\
&\quad 58.71 \\
&\quad -6.21 \cdot x_1 - 6.12 \cdot x_2 + 40.51 \cdot x_3 + 5.00 \cdot x_4 + 2.93 \cdot x_5 \\
&\quad +2.80 \cdot x_1x_2 + 5.69 \cdot x_1x_3 - 1.60 \cdot x_1x_4 - 0.87 \cdot x_1x_5 + 5.95 \cdot x_2x_3 \\
&\quad -3.69 \cdot x_2x_4 - 3.12 \cdot x_2x_5 - 4.54 \cdot x_3x_4 - 2.81 \cdot x_3x_5 + 1.40 \cdot x_4x_5
\end{aligned} \tag{6.8}$$

	static-idealized	**static-random**	**dynamic-random**	**dynamic-targeted**
SST	58851.7	46133.6	62612.1	60625.7
SSE	1523.1	2440.6	908.0	1238.8
R^2	0.97	0.95	0.99	0.98
α_0	59.76	33.14	52.08	56.34
% contrib. x_1	1.64	0.85	0.37	1.19
% contrib. x_2	2.28	5.0e-2	0.85	1.65
% contrib. x_3	85.04	72.35	94.01	89.04
% contrib. x_4	1.18	7.29	0.81	1.12
% contrib. x_5	0.45	3.38	0.62	0.4
% contrib. x_1x_2	0.37	6.0e-2	0.33	0.44
% contrib. x_1x_3	1.64	1.14	0.5	1.38
% contrib. x_1x_4	5.0e-2	2.0e-2	3.0e-2	9.0e-2
% contrib. x_1x_5	0.0	1.08	5.0e-2	1.0e-2
% contrib. x_2x_3	1.83	0.16	0.41	1.05
% contrib. x_2x_4	0.56	1.0e-2	0.17	0.37
% contrib. x_2x_5	0.44	1.0e-2	0.1	0.24
% contrib. x_3x_4	0.85	6.5	5.0e-2	0.53
% contrib. x_3x_5	0.32	1.87	3.0e-2	8.0e-2
% contrib. x_4x_5	2.0e-2	1.64	0.0	0.0

Table 6.4: Main RSM results for the satisfaction rates of all considered schemes for 150 WBSNs.

The fitted models for $\delta = 150$:

$$
\begin{aligned}
&Y_{\text{static-idealized}} = \\
&\quad 59.76 \\
&\quad -5.49 \cdot x_1 - 6.47 \cdot x_2 + 39.55 \cdot x_3 + 4.66 \cdot x_4 + 2.89 \cdot x_5 \\
&\quad +2.61 \cdot x_1x_2 + 5.50 \cdot x_1x_3 - 0.96 \cdot x_1x_4 - 0.29 \cdot x_1x_5 + 5.81 \cdot x_2x_3 \\
&\quad -3.20 \cdot x_2x_4 - 2.84 \cdot x_2x_5 - 3.96 \cdot x_3x_4 - 2.44 \cdot x_3x_5 + 0.58 \cdot x_4x_5
\end{aligned} \tag{6.9}
$$

$$
\begin{aligned}
&Y_{\text{static-random}} = \\
&\quad 33.14 \\
&\quad +3.49 \cdot x_1 + 0.81 \cdot x_2 + 32.30 \cdot x_3 + 10.25 \cdot x_4 + 6.98 \cdot x_5 \\
&\quad +0.91 \cdot x_1x_2 + 4.06 \cdot x_1x_3 + 0.56 \cdot x_1x_4 + 3.94 \cdot x_1x_5 + 1.50 \cdot x_2x_3 \\
&\quad +0.37 \cdot x_2x_4 - 0.42 \cdot x_2x_5 + 9.68 \cdot x_3x_4 + 5.20 \cdot x_3x_5 - 4.86 \cdot x_4x_5
\end{aligned} \tag{6.10}
$$

$$
\begin{aligned}
&Y_{\text{dynamic-random}} = \\
&\quad 52.08 \\
&\quad -2.68 \cdot x_1 - 4.07 \cdot x_2 + 42.89 \cdot x_3 + 3.99 \cdot x_4 + 3.49 \cdot x_5 \\
&\quad +2.53 \cdot x_1x_2 + 3.13 \cdot x_1x_3 - 0.78 \cdot x_1x_4 - 0.94 \cdot x_1x_5 + 2.82 \cdot x_2x_3 \\
&\quad -1.82 \cdot x_2x_4 - 1.38 \cdot x_2x_5 - 0.97 \cdot x_3x_4 - 0.80 \cdot x_3x_5 - 0.14 \cdot x_4x_5
\end{aligned} \tag{6.11}
$$

$$
\begin{aligned}
&Y_{\text{dynamic-targeted}} = \\
&\quad 56.34 \\
&\quad -4.75 \cdot x_1 - 5.59 \cdot x_2 + 41.07 \cdot x_3 + 4.60 \cdot x_4 + 2.75 \cdot x_5 \\
&\quad +2.90 \cdot x_1x_2 + 5.12 \cdot x_1x_3 - 1.29 \cdot x_1x_4 - 0.37 \cdot x_1x_5 + 4.46 \cdot x_2x_3 \\
&\quad -2.66 \cdot x_2x_4 - 2.12 \cdot x_2x_5 - 3.18 \cdot x_3x_4 - 1.22 \cdot x_3x_5 + 0.08 \cdot x_4x_5
\end{aligned} \tag{6.12}
$$

	static-idealized	**static-random**	**dynamic-random**	**dynamic-targeted**
SST	59342.9	36979.0	59159.2	59651.2
SSE	1324.6	2038.0	1368.8	1014.4
R^2	0.98	0.94	0.98	0.98
α_0	58.28	26.16	44.25	54.28
% contrib. x_1	1.41	4.66	0.52	1.43
% contrib. x_2	1.8	0.25	7.0e-2	1.15
% contrib. x_3	87.71	57.81	89.44	90.81
% contrib. x_4	1.04	10.41	2.96	1.31
% contrib. x_5	0.5	2.95	1.71	0.5
% contrib. x_1x_2	0.38	4.0e-2	0.0	0.4
% contrib. x_1x_3	1.34	4.85	0.78	0.77
% contrib. x_1x_4	4.0e-2	7.0e-2	0.46	2.0e-2
% contrib. x_1x_5	0.0	1.71	8.0e-2	2.0e-2
% contrib. x_2x_3	1.32	0.33	0.11	0.76
% contrib. x_2x_4	0.36	7.0e-2	8.0e-2	0.3
% contrib. x_2x_5	0.42	3.0e-2	7.0e-2	0.34
% contrib. x_3x_4	0.49	9.96	1.38	0.19
% contrib. x_3x_5	0.29	1.81	0.29	4.0e-2
% contrib. x_4x_5	0.0	1.27	0.45	0.0

Table 6.5: Main RSM results for the satisfaction rates of all considered schemes for 200 WBSNs.

The fitted models for $\delta = 200$:

$$
\begin{aligned}
Y_{\text{static-idealized}} = & \\
& 58.28 \\
& -5.11 \cdot x_1 - 5.77 \cdot x_2 + 40.33 \cdot x_3 + 4.39 \cdot x_4 + 3.03 \cdot x_5 \\
& +2.64 \cdot x_1x_2 + 4.99 \cdot x_1x_3 - 0.82 \cdot x_1x_4 - 0.16 \cdot x_1x_5 + 4.96 \cdot x_2x_3 \\
& -2.57 \cdot x_2x_4 - 2.80 \cdot x_2x_5 - 3.00 \cdot x_3x_4 - 2.31 \cdot x_3x_5 + 0.29 \cdot x_4x_5
\end{aligned} \tag{6.13}
$$

$$
\begin{aligned}
Y_{\text{static-random}} = & \\
& 26.16 \\
& +7.33 \cdot x_1 + 1.70 \cdot x_2 + 25.85 \cdot x_3 + 10.97 \cdot x_4 + 5.83 \cdot x_5 \\
& +0.67 \cdot x_1x_2 + 7.49 \cdot x_1x_3 + 0.87 \cdot x_1x_4 + 4.45 \cdot x_1x_5 + 1.96 \cdot x_2x_3 \\
& +0.93 \cdot x_2x_4 - 0.63 \cdot x_2x_5 + 10.73 \cdot x_3x_4 + 4.57 \cdot x_3x_5 - 3.83 \cdot x_4x_5
\end{aligned} \tag{6.14}
$$

$$
\begin{aligned}
Y_{\text{dynamic-random}} = & \\
& 44.25 \\
& +3.09 \cdot x_1 - 1.17 \cdot x_2 + 40.66 \cdot x_3 + 7.40 \cdot x_4 + 5.63 \cdot x_5 \\
& +0.10 \cdot x_1x_2 + 3.80 \cdot x_1x_3 - 2.91 \cdot x_1x_4 - 1.24 \cdot x_1x_5 + 1.44 \cdot x_2x_3 \\
& -1.21 \cdot x_2x_4 - 1.13 \cdot x_2x_5 + 5.05 \cdot x_3x_4 + 2.33 \cdot x_3x_5 - 2.89 \cdot x_4x_5
\end{aligned} \tag{6.15}
$$

$$
\begin{aligned}
Y_{\text{dynamic-targeted}} = & \\
& 54.28 \\
& -5.16 \cdot x_1 - 4.62 \cdot x_2 + 41.14 \cdot x_3 + 4.94 \cdot x_4 + 3.05 \cdot x_5 \\
& +2.73 \cdot x_1x_2 + 3.80 \cdot x_1x_3 - 0.63 \cdot x_1x_4 + 0.57 \cdot x_1x_5 + 3.77 \cdot x_2x_3 \\
& -2.37 \cdot x_2x_4 - 2.53 \cdot x_2x_5 - 1.89 \cdot x_3x_4 - 0.89 \cdot x_3x_5 - 0.27 \cdot x_4x_5
\end{aligned} \tag{6.16}
$$

	static-idealized	**static-random**	**dynamic-random**	**dynamic-targeted**
SST	54563.8	29760.2	49048.3	53443.7
SSE	1769.3	1823.8	1949.2	1825.4
R^2	0.97	0.94	0.96	0.97
α_0	38.75	20.15	33.01	37.09
% contrib. x_1	2.13	10.8	2.1	2.0
% contrib. x_2	0.0	0.61	3.0e-2	4.0e-2
% contrib. x_3	75.74	43.23	68.82	75.38
% contrib. x_4	7.06	10.26	9.72	6.86
% contrib. x_5	1.56	3.02	1.98	1.83
% contrib. x_1x_2	0.0	8.0e-2	3.0e-2	6.0e-2
% contrib. x_1x_3	2.11	10.79	2.09	2.5
% contrib. x_1x_4	1.77	0.86	0.7	1.18
% contrib. x_1x_5	5.0e-2	2.2	0.34	9.0e-2
% contrib. x_2x_3	3.0e-2	0.65	0.0	0.0
% contrib. x_2x_4	1.0e-2	0.27	0.0	0.0
% contrib. x_2x_5	1.0e-2	9.0e-2	1.0e-2	0.1
% contrib. x_3x_4	5.89	10.09	8.94	5.59
% contrib. x_3x_5	0.45	2.19	0.87	0.71
% contrib. x_4x_5	0.83	0.74	1.43	1.32

Table 6.6: Main RSM results for the satisfaction rates of all considered schemes for 250 WBSNs.

The fitted models for $\delta = 250$:

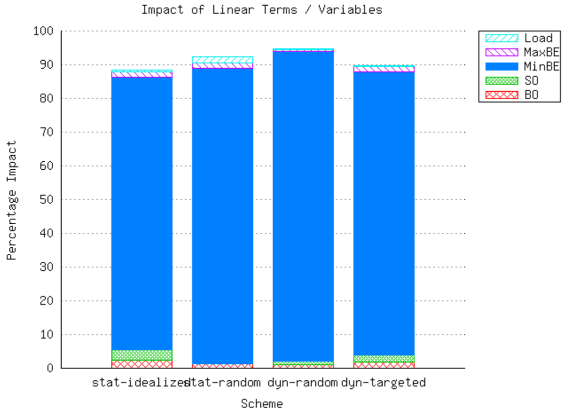
$$
\begin{aligned}
&Y_{\text{static-idealized}} = \\
&\quad 38.75 \\
&\quad +6.03 \cdot x_1 - 0.09 \cdot x_2 + 35.94 \cdot x_3 + 10.97 \cdot x_4 + 5.16 \cdot x_5 \\
&\quad +0.23 \cdot x_1x_2 + 6.00 \cdot x_1x_3 - 5.50 \cdot x_1x_4 + 0.90 \cdot x_1x_5 + 0.75 \cdot x_2x_3 \\
&\quad -0.36 \cdot x_2x_4 - 0.29 \cdot x_2x_5 + 10.02 \cdot x_3x_4 + 2.76 \cdot x_3x_5 - 3.76 \cdot x_4x_5
\end{aligned} \tag{6.17}
$$

$$
\begin{aligned}
&Y_{\text{static-random}} = \\
&\quad 20.15 \\
&\quad +10.02 \cdot x_1 + 2.38 \cdot x_2 + 20.05 \cdot x_3 + 9.77 \cdot x_4 + 5.30 \cdot x_5 \\
&\quad +0.88 \cdot x_1x_2 + 10.02 \cdot x_1x_3 + 2.83 \cdot x_1x_4 + 4.52 \cdot x_1x_5 + 2.46 \cdot x_2x_3 \\
&\quad +1.60 \cdot x_2x_4 - 0.93 \cdot x_2x_5 + 9.69 \cdot x_3x_4 + 4.52 \cdot x_3x_5 - 2.63 \cdot x_4x_5
\end{aligned} \tag{6.18}
$$

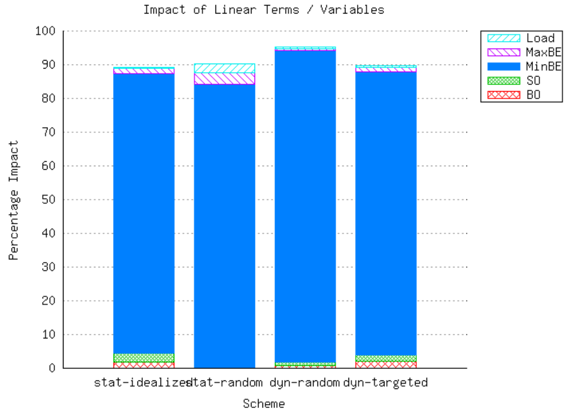
$$
\begin{aligned}
&Y_{\text{dynamic-random}} = \\
&\quad 33.01 \\
&\quad +5.67 \cdot x_1 - 0.72 \cdot x_2 + 32.48 \cdot x_3 + 12.21 \cdot x_4 + 5.51 \cdot x_5 \\
&\quad +0.70 \cdot x_1x_2 + 5.65 \cdot x_1x_3 - 3.27 \cdot x_1x_4 + 2.29 \cdot x_1x_5 - 0.22 \cdot x_2x_3 \\
&\quad -0.22 \cdot x_2x_4 - 0.46 \cdot x_2x_5 + 11.70 \cdot x_3x_4 + 3.65 \cdot x_3x_5 - 4.68 \cdot x_4x_5
\end{aligned} \tag{6.19}
$$

$$
\begin{aligned}
&Y_{\text{dynamic-targeted}} = \\
&\quad 37.09 \\
&\quad +5.77 \cdot x_1 - 0.79 \cdot x_2 + 35.48 \cdot x_3 + 10.71 \cdot x_4 + 5.53 \cdot x_5 \\
&\quad +0.96 \cdot x_1x_2 + 6.47 \cdot x_1x_3 - 4.44 \cdot x_1x_4 + 1.21 \cdot x_1x_5 + 0.08 \cdot x_2x_3 \\
&\quad +0.10 \cdot x_2x_4 - 1.32 \cdot x_2x_5 + 9.67 \cdot x_3x_4 + 3.45 \cdot x_3x_5 - 4.70 \cdot x_4x_5
\end{aligned} \tag{6.20}
$$

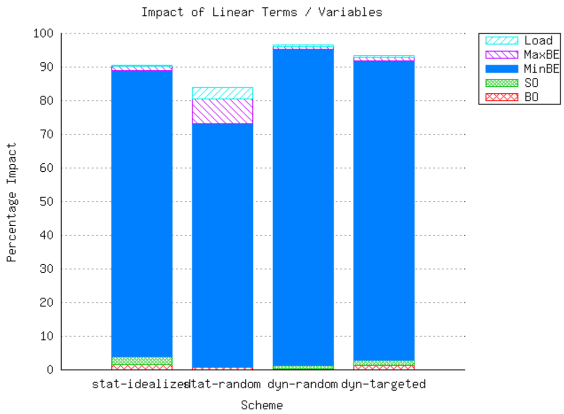
Clearly, our results indicate that the *macMinBE* parameter (and to a lesser extent *macMaxBE*) plays a decisive role in the achievable performance. From the regression equations (Equations 6.13 to 6.20) the term for x_3 (*macMinBE*) enters with a



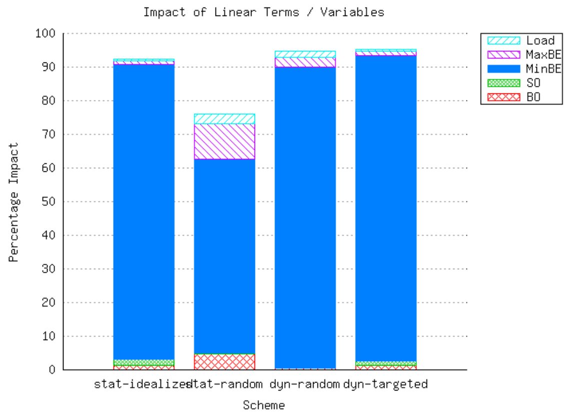
(a) Impact of factors on satisfaction rate, WBSN-density = 50



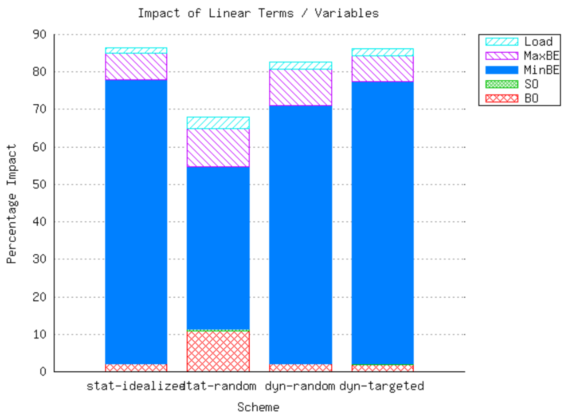
(b) Impact of factors on satisfaction rate, WBSN-density = 100



(c) Impact of factors on satisfaction rate, WBSN-density = 150



(d) Impact of factors on satisfaction rate, WBSN-density = 200



(e) Impact of factors on satisfaction rate, WBSN-density = 250

Figure 6.5: Percentage impacts of different factors on satisfaction rate in the presence of varying internal interference.

# **WBSNs**	**static-idealized**	**static-random**	**dynamic-random**	**dynamic-targeted**
50	62.11	46.75	56.77	59.44
100	61.01	41.26	54.57	58.71
150	59.76	33.14	52.08	56.34
200	58.28	26.16	44.25	54.28
250	38.75	20.15	33.01	37.09

Table 6.7: Intercept values for all considered schemes and different numbers of WBSNs

positive sign, so to achieve better satisfaction rate we need to choose larger values of *macMinBE*. The *macMinBE* parameter determines the initial average waiting time after which a sensor node performs a carrier-sense operation for a new packet, so it is a measure for how aggressively a node tries to send data. Longer initial waiting times lead to fewer collisions so that more channel resources are left for useful transmissions even in high node densities.

6.4 Carrying Capacity

In Table 6.8 we show the results for the carrying capacity of the different schemes (see Section 6.1). To obtain the carrying capacity, we simulate a given scheme with WBSN numbers taken from the set $\mathcal{W}$ so that for each of these numbers $w \in \mathcal{W}$ a number of 64 replications is carried out. For each replication we calculate the number of satisfied WBSNs, and we compute the average of these numbers over all replications, giving us the average percentage of satisfied WBSNs for a given number $w \in \mathcal{W}$ of WBSNs. After collecting these averages for all WBSN numbers from $\mathcal{W}$ we calculate a regression curve (a second-order polynomial) allowing to interpolate the average number of satisfied WBSNs between the points given by $\mathcal{W}$, and the carrying capacity is determined as the point / number of WBSNs where this regression curve crosses the 95% line. Please note that we have resorted to this interpolation approach since otherwise simulation times would have been prohibitively long. We show the carrying capacity for the following parameters: $BO = 6$, $SO = 4$, packet inter-arrival time of one second, $macMinBE = 3$, and $macMaxBE = 5$ (the latter two are the default values suggested by the standard). It is interesting to note that here the difference between the dynamic-targeted-hopping and the static-idealized scheme is more pronounced. Again, we essentially attribute the difference between these two schemes to the inability of the dynamic-targeted-hopping scheme to adjust the phases of the WBSNs sharing the same channel.

Table 6.8: Carrying capacity

Schemes	**Carrying Capacity**
static-random	19
static-initial-choice	20
dynamic-random-hopping	93
dynamic-targeted-hopping	137
static-idealised	155

6.5 Packet Success Rate

The main focus of this thesis is on performance measures geared towards applications having some notion of "acceptable" and "unacceptable" packet loss performance and using a particular threshold to distinguish between these (here we use a packet success rate of 95% to mark a WBSN as satisfied). For applications which do not have a natural threshold it is interesting to get some insight into the packet success rate performance of the different schemes. We have again carried out a RSM analysis of all four schemes for the packet success rate (see Section 6.1). In Table 6.9 we show for all considered numbers of WBSNs and all considered schemes the intercept values α_0 for the packet success rate. The following points are interesting:

- While not shown here, again the chosen second-order model has a very high R^2 value (≥ 0.98) for all schemes and all numbers of WBSNs, so it explains almost all of the observed variation.

# **WBSNs**	*static-random*	*static-idealized*	*dynamic-random*	*dynamic-targeted*
50	85.95	89.64	86.84	88.46
100	84.37	88.21	85.28	86.81
150	81.85	86.4	82.86	84.75
200	79.14	84.36	80.64	82.49
250	72.31	78.92	74.1	76.5

Table 6.9: Intercept values for the packet success rate for all considered schemes and different numbers of WBSNs

# **WBSNs**	*static-idealized*	*static-random*	*dynamic-random*	*dynamic-targeted*
50	4.02	3.67	4.06	3.92
100	4.35	3.78	4.26	4.04
150	4.63	3.51	4.4	3.99
200	4.99	3.96	4.86	4.5
250	5.9	4.29	5.5	4.79

Table 6.10: Intercept values for the packet success rate standard deviation for all considered schemes and different numbers of WBSNs

- The intercept values α_0 of the different schemes are closer to each other than we have found for the satisfaction rate, and for the same scheme their range is relatively smaller. This suggests that introducing sharp thresholds makes differences between the schemes more pronounced.

Another important aspect of the packet success rate is how different it can be for different WBSNs in the same scenario, i.e. how fair the packet success rate allocation to WBSNs is. To look into this we have carried out the RSM analysis for the average standard deviations of the packet success rates. The intercept values α_0 for this are shown in Table 6.10. It can be seen that generally the average standard deviation does not exceed 6%, which is relatively small compared to the average packet success rate percentages reported in Table 6.9, and suggests that on average the differences in packet success rates among WBSNs are minor. This can be attributed to the fact that all WBSNs are configured in the same way.

7 Simulation-based Performance Evaluation of Active Scheme

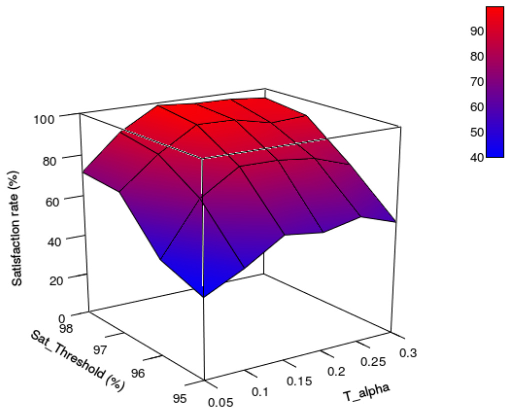
7.1 Performance Evaluation of Passive and Active Schemes: Static Environment

Before comparing DPS scheme with the passive schemes, a simulation study is conducted to determine the the values of both T_α and $T_{threshold}$ using Table 7.1.

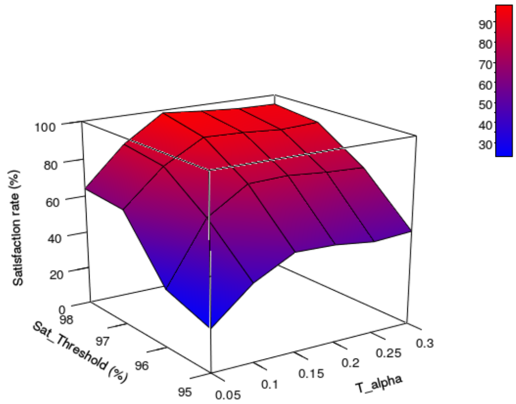
Table 7.1: Value variation

Parameter	**values**	**step**
T_alpha	0.05 to 0.3	0.05
satisfaction threshold	95% to 98%	1%

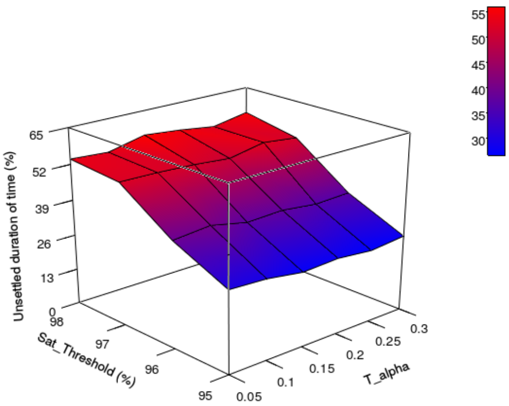
In this simulation study 64 simulation runs were carried out in which a number of WBSNs $\delta \in \Delta = \{13, 16\}$ were located in one channel and the satisfaction rate, percentage of time spent in settled and in unsettled states are determined. The rest of the simulation specifications are as the same as previously mentioned in Table 3.1. Since we were interested to explore the performance of the proposed dynamic-phase-shifting algorithm, only one channel is considered for this particular study. Moreover, in order to create a scenario where WBSNs experience mutual interference, $\delta \in \Delta = \{13, 16\}$ are considered which are reasonably large and represents $\delta \in \Delta = \{200, 250\}$ when 16 channels are used. Figure 7.1 shows the obtained results of varying the values of both T_α and satisfaction threshold parameters.



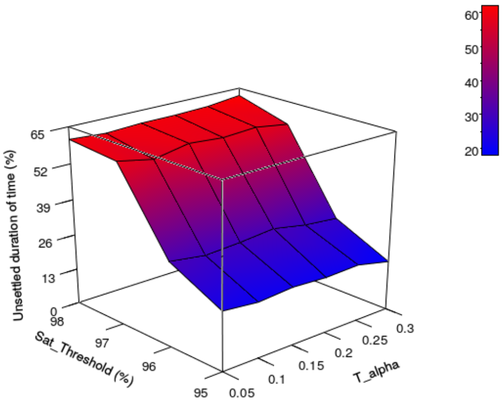
(a) Satisfaction rate, WBSN-density = 13



(b) Satisfaction rate, WBSN-density = 16



(c) Average percentage of time spent in unsettled state, WBSN-density = 13



(d) Average percentage of time spent in settled state, WBSN-density = 16

Figure 7.1: Performance comparison of the dynamic-phase-jumping scheme while varying the values of T_alpha and satisfaction threshold

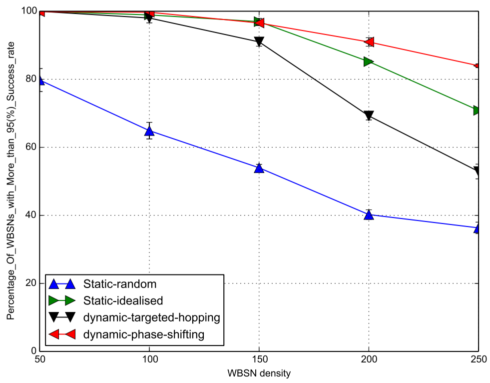
The presented results highlights the following points:

Figures 7.1a and 7.1b suggest that the lower values of T_α and satisfaction threshold (lower than 0.15 and 98%, respectively) results in significantly lower satisfaction rate. Furthermore, $T_\alpha = 0.15$ offers the highest satisfaction rate among other values that are above 0.15. The presented results show that the combination of $T_\alpha = 0.15$ and satisfaction threshold = 98% offers the highest satisfaction rate.

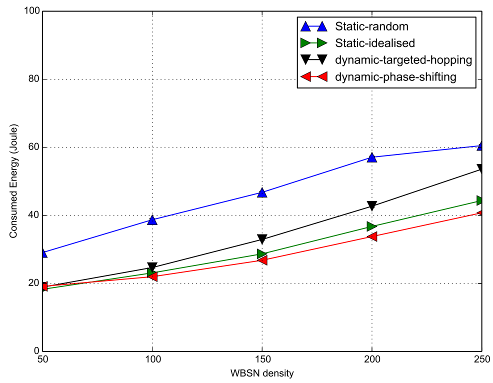
Figure 7.1d, presents the average percentage of time spent in unsettled state. The interesting point about these graphs is the strong impact of the $T_{threshold}$ on the amount of time spent in unsettled states, whereas the variation of T_α does not noticeably effect the average amount of time spent in either states. When satisfaction threshold = 98%, the transition from settled to unsettled and vice versa seems to happen more frequently compared to the lower values the satisfaction threshold. This can be observed by looking at Figure 7.1d that shows the average percentage duration of time that WBSNs spent in unsettled state approximately about 58.8% when the satisfaction threshold is 98%, whereas it decreases to approximately 20.3% percent when the satisfaction threshold is 95%.

This suggests that having WBSNs to more frequently shift their phases not only results in the higher satisfaction rate but also it shows that more WBSNs on average are involved in the process of transitioning from settled to unsettled and vice versa which can result in settling in a suitable time slot at the early stage of activation and benefiting from higher percentage of the successful transmission of data packets. It should be mentioned that minimising the difference between the amount of time spent in settled and unsettled states when the satisfaction threshold = 98% is the matter of fairness issue and is suggested as a future work.

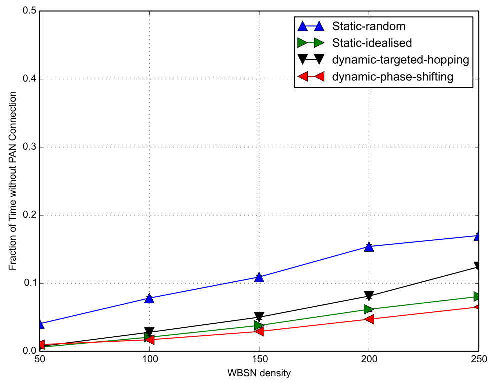
As a reminder, in DPS scheme, occupants of the same channel communicate with each other to share critical information such as number of detected WBSNs in the current channel. This information sharing occurs using the payload of the beacon packets and no extra packets (e.g. command packet) is used for this purpose. Frequency adaptation and phase adaptation are the two procedures that are performed in parallel with minimum interaction. When the performance of a WBSN has degraded below the threshold, it utilises the phase adaptation procedure to shift its beacon to another randomly selected time slot, and switches to another operating frequency whenever it detects a channel with lower (difference of at least two WBSNs) occupants. Figure 7.3 shows the comparison of the performance of the static-random, dynamic-targeted-hopping, static-idealized and DPS schemes. System parameters are configured using the values presented in Table 3.1. Please note that the simulation time in this experiment is increased to 5000 seconds which consequently make a sensor device to generate 5000 data packets. This change allows us to examine the behaviour of considered schemes and provide a comparison between them in longer duration.



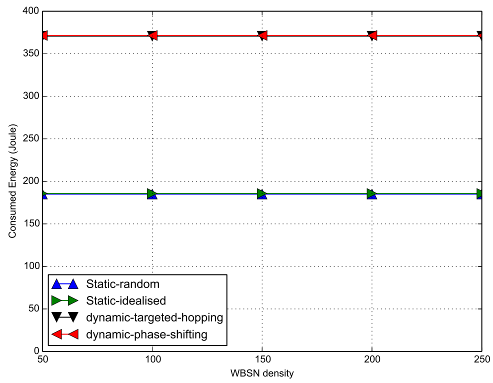
(a) Satisfaction rate



(b) Sensor energy consumption



(c) Orphan period



(d) Coordinator energy consumption

Figure 7.2: Performance comparison between DPS scheme and previously-mentioned passive schemes

The presented results highlights the following points:

- Interestingly, the DPS scheme can significantly improve the satisfaction rate of the static-idealized scheme. In static-idealized scheme WBSNs are not able to change their phases. Therefore, as the number of WBSNs becomes larger in the channel, higher overlapping ratio of their active periods will be inevitable, whereas in DPS scheme, they can shift their phases to other time slots. This phase-shifting procedure is repeatedly performed by the WBSN (in unsettled state) until it becomes satisfied (success rate $\geq$ the satisfaction threshold). In the DPS scheme, each time that the active period of a settled WBSN overlaps with the active periods of (jumping) unsettled WBSNs, it increases its jumping probability and becomes unsettled and performs the phase-shifting procedure only when its jumping probability exceeds the $T_{threshold}$. This implies that a subset of WBSNs would find their time slot relatively early (enter to settled state) and experience a success rate above the satisfaction threshold while other WBSNs must jump and look for their suitable time slot for a while. This is mainly the reason to the increased satisfaction rate of the DPS scheme compared to the static-idealized when $\delta \in \Delta = \{200, 250\}$.

- The fraction of time without PAN coordinator and the sensor energy consumption diagrams show a slight improvement compared to static-idealized scheme. However, the significantly higher coordinator energy consumption in the DPS scheme shows that the improvement of satisfaction rate comes at higher cost of energy consumption of coordinators.

- Considering the same amount of coordinator energy consumption of the DPS and the dynamic-targeted-hopping schemes, it can be concluded that the amount of energy consumed by performing the DPS algorithm is negligible.

7.1.1 Carrying Capacity

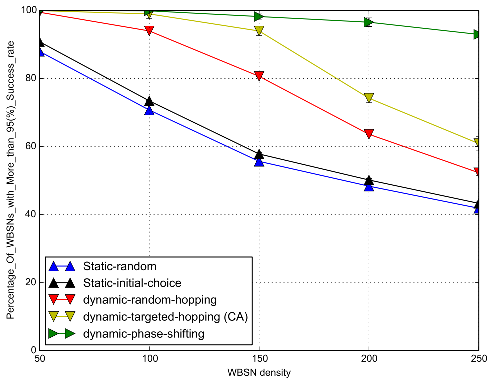
Carrying capacity is another main performance measure in this study. This performance measure indicates the largest number of WBSNs that can be gathered at the very close vicinity in such a way that only negligible number of them experience performance degradation. In order to see how this performance measure is obtained please refer to Chapter 6 Section 6.4. Table 7.3 shows the carrying capacity for all given schemes. Clearly, DPS scheme outperforms all other schemes in terms of carrying capacity as well. We have managed to improve the carrying capacity from 19 WBSNs that are uniformly distributed over 16 available channels (static-random scheme) to 165 WBSNs (DPS scheme).

Table 7.2: Carrying capacity – Static Environment

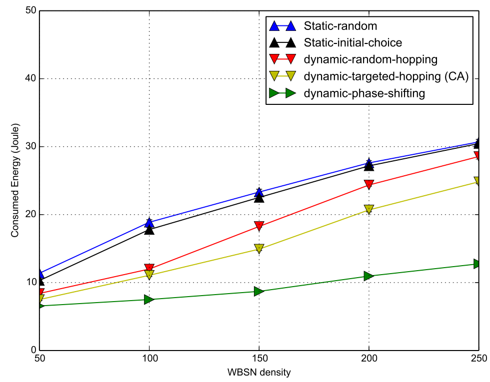
Schemes	**Carrying Capacity**
static-random (lower-band)	19
static-initial-choice	20
dynamic-random-hopping	93
dynamic-targeted-hopping	137
static-idealised (hypothetical upper-band)	155
DPS	165

7.2 Performance Evaluation of Practical Passive and Active Schemes: Dynamic Environment

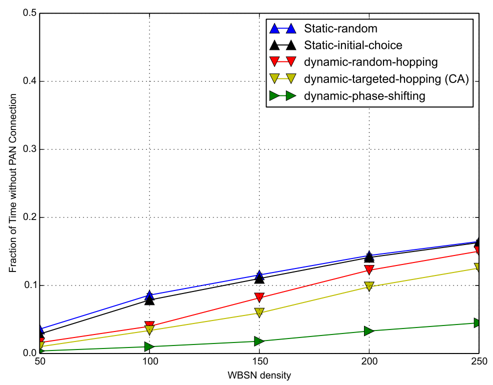
As a reminder, in our simulated dynamic environment, a WBSN is forced to switch off after a random time selected uniformly from [500BP, 1000BP], where BP is the Beacon Period (in seconds). It is switched back on after a random time selected uniformly from [400CAP, 600CAP]. This configuration emulates dynacmi population / mobility where WBSNs experience different intensity-levels of mutual interference over time. Clearly, in this configuration, it is likely that a WBSN starts its activity in a new time slot. Therefore, the overlapping ratio of WBSN's active periods becomes more likely to decrease. Eventually, higher satisfaction and carrying capacity is observed. Furthermore, since WBSNs were continuously switched off, less energy is consumed compared to static environment scenarios. Please note that the static-idealized scheme is excluded from this experiment due to its impracticality and it was only designed for static environment. The presented results highlight the following points:



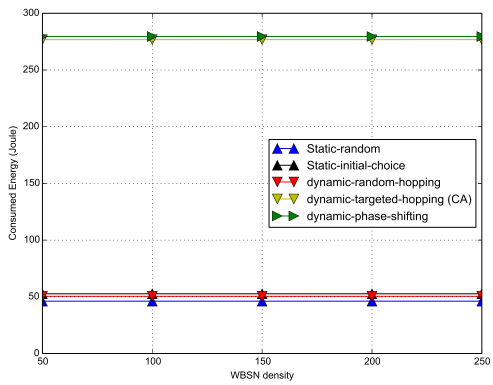
(a) Satisfaction rate



(b) Sensor energy consumption



(c) Orphan period



(d) Coordinator energy consumption

Figure 7.3: The performance evaluation of all practical schemes in Dynamic Environment

- In this thesis, static environment is the worst case scenario compared to dynamic environment in which it is possible for WBSNs to resume their activity in some other phases / time slots. This highlights the necessity of focusing on the static environment and generically improve the performance gain of WBSNs, so that by extension, WBSNs can achieve better performance gain in dynamic environment as well.

- Clearly, DPS scheme offers a highest satisfaction rate amongst other practical passive schemes. This by far improvement can be directly attributed to the ability of shifting the beacon to another phase when it is required.

- Considering the carrying capacity of both practical passive and active schemes, it is shown that the proposed DPS scheme (with its current internal parameter settings) achieved the largest number of satisfied WBSNs in the considered dynamic environment. This is simply due to better utilisation of the channel when other WBSNs are switched off. Please note that better channel utilisation here means that a WBSN keeps shifting its phase to other phases until a phase is found in which the network performance does not degrade below the threshold.

Table 7.3: Carrying capacity – Dynamic Environment

Schemes	**Carrying Capacity**
static-random (lower-band)	20
static-initial-choice	23
dynamic-random-hopping	94
dynamic-targeted-hopping	141
DPS	225

7.3 Active Scheme And the Sensitivity Analysis of System Parameters

In this section we have analysed the sensitivity of the performance measure (satisfaction rate) against the variation of the previously-mentioned system parameters (see Table 5.1). The results are summarised in Table 7.4 followed by the best fit model for each $\delta \in \Delta$. Figure 7.4 also shows the more visualisation of the contribution percentage of each considered system parameter to the final performance of WBSNs.

Table 7.4: Main RSM results for the satisfaction rates of different number of WBSNs

	WBSN = 50	**WBSN = 100**	**WBSN = 150**	**WBSN = 200**	**WBSN = 250**
SST	50666.37	52986.19	50506.36	54164.33	52639.32
SSE	1519.9	1059.7	1515.1	1624.9	2105.5
R^2	0.97	0.98	0.97	0.97	0.96
α_0	63.87	62.33	60.41	60.53	41.63
% contrib. x_1	2.84	1.92	1.28	1.69	2.05
% contrib. x_2	3.89	3.12	3.71	2.11	8.41e-5
% contrib. x_3	80.85	83.79	82.97	87.52	78.57
% contrib. x_4	1.94	2.03	3.40	1.70	7.50
% contrib. x_5	0.45	0.47	0.35	0.37	1.72
% contrib. x_1x_2	0.39	0.25	0.73	0.28	1.46e-5
% contrib. x_1x_3	2.60	1.73	3.33	1.75	2.33
% contrib. x_1x_4	0.01	0.05	0.55	0.10	1.72
% contrib. x_1x_5	0.01	3.25e-5	0.03	0.02	0.04
% contrib. x_2x_3	3.59	2.90	1.29	1.67	0.02
% contrib. x_2x_4	0.83	1.03	0.26	0.52	0.01
% contrib. x_2x_5	0.38	0.41	0.67	0.65	0.01
% contrib. x_3x_4	1.72	1.78	1.04	1.27	4.90
% contrib. x_3x_5	0.40	0.41	0.32	0.27	0.37
% contrib. x_4x_5	0.02	0.03	1.37e-5	2.36e-5	0.69

The fitted models for $\delta = 50$:

$$\begin{aligned}
&Y_{\text{dynamic-phase-shifting}} = \\
&\quad 63.87 \\
&\quad -6.71 \cdot x_1 - 7.85 \cdot x_2 + 35.77 \cdot x_3 + 5.55 \cdot x_4 + 2.69 \cdot x_5 \\
&\quad +2.49 \cdot x_1x_2 + 6.41 \cdot x_1x_3 - 0.47 \cdot x_1x_4 + 0.49 \cdot x_1x_5 + 7.54 \cdot x_2x_3 \\
&\quad -3.62 \cdot x_2x_4 - 2.48 \cdot x_2x_5 - 5.22 \cdot x_3x_4 - 2.52 \cdot x_3x_5 + 0.68 \cdot x_4x_5
\end{aligned} \tag{7.1}$$

The fitted models for $\delta = 100$:

$$\begin{aligned}
&Y_{\text{dynamic-phase-shifting}} = \\
&\quad 62.33 \\
&\quad -5.64 \cdot x_1 - 7.19 \cdot x_2 + 37.24 \cdot x_3 + 5.80 \cdot x_4 + 2.81 \cdot x_5 \\
&\quad +2.06 \cdot x_1x_2 + 5.36 \cdot x_1x_3 - 0.91 \cdot x_1x_4 + 0.23 \cdot x_1x_5 + 6.93 \cdot x_2x_3 \\
&\quad -4.13 \cdot x_2x_4 - 2.62 \cdot x_2x_5 - 5.43 \cdot x_3x_4 - 2.63 \cdot x_3x_5 + 0.73 \cdot x_4x_5
\end{aligned} \tag{7.2}$$

The fitted models for $\delta = 150$:

$$\begin{aligned}
&Y_{\text{dynamic-phase-shifting}} = \\
&\quad 60.41 \\
&\quad -4.51 \cdot x_1 - 7.65 \cdot x_2 + 36.18 \cdot x_3 + 7.33 \cdot x_4 + 2.35 \cdot x_5 \\
&\quad +3.40 \cdot x_1x_2 + 7.25 \cdot x_1x_3 - 2.94 \cdot x_1x_4 + 0.75 \cdot x_1x_5 + 4.52 \cdot x_2x_3 \\
&\quad -2.03 \cdot x_2x_4 - 3.26 \cdot x_2x_5 - 4.05 \cdot x_3x_4 - 2.26 \cdot x_3x_5 + 0.14 \cdot x_4x_5
\end{aligned} \tag{7.3}$$

The fitted models for $\delta = 200$:

$$
\begin{aligned}
&Y_{\text{dynamic-phase-shifting}} = \\
&\quad 60.53 \\
&\quad -5.36 \cdot x_1 - 5.98 \cdot x_2 + 38.49 \cdot x_3 + 5.36 \cdot x_4 + 2.51 \cdot x_5 \\
&\quad +2.19 \cdot x_1x_2 + 5.45 \cdot x_1x_3 - 1.34 \cdot x_1x_4 + 0.69 \cdot x_1x_5 + 5.32 \cdot x_2x_3 \\
&\quad -2.96 \cdot x_2x_4 - 3.32 \cdot x_2x_5 - 4.64 \cdot x_3x_4 - 2.14 \cdot x_3x_5 + 0.20 \cdot x_4x_5
\end{aligned} \tag{7.4}
$$

The fitted models for $\delta = 250$:

$$
\begin{aligned}
&Y_{\text{dynamic-phase-shifting}} = \\
&\quad 41.63 \\
&\quad +5.80 \cdot x_1 - 0.37 \cdot x_2 + 35.95 \cdot x_3 + 11.11 \cdot x_4 + 5.33 \cdot x_5 \\
&\quad +0.15 \cdot x_1x_2 + 6.20 \cdot x_1x_3 - 5.32 \cdot x_1x_4 + 0.84 \cdot x_1x_5 + 0.59 \cdot x_2x_3 \\
&\quad -0.43 \cdot x_2x_4 - 0.50 \cdot x_2x_5 + 8.98 \cdot x_3x_4 + 2.48 \cdot x_3x_5 - 3.37 \cdot x_4x_5
\end{aligned} \tag{7.5}
$$

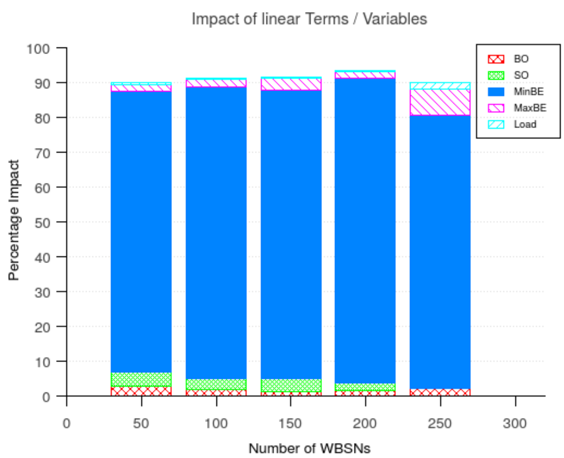


Figure 7.4: Impact of factors on satisfaction rate in DPS scheme for all $\delta \in \Delta$

The presented results highlights the following points:

- For each $\delta \in \Delta$ the R values for the DPS scheme indicates that the regression anstaz covers almost all the observed variations. This again shows that the presented incomplete model – in which all interactions between three or more factors are ignored – is in good approximation.

- DPS scheme achieves the highest average satisfaction rate compared to static-idealized and – by extension – dynamic-targeted-hopping schemes. Considering Table 7.4, it can be observed that for this scheme the linear terms alone have already explained more than approximately 80% of the observed variations[1]. Furthermore, for each $\delta \in \Delta$ the factor x_3 (*macMinBE*) is by far the most influential factor for the satisfaction rate. The impact of the factor x_4 becomes noticeable when $\delta \in \Delta$, whereas the impact of other factors is comparatively negligible. The obtained results suggest that the factor x_3 mainly has the most impact of the satisfaction rate and the adaptation or at least careful configuration of this parameter can lead to higher satisfaction rate.

- By comparing the intercept values of the DPS scheme and the previously-mentioned passive schemes, it can be observed that the DPS scheme in which a WBSN is able to change both operating frequencies and time / phases, is the overall best scheme.

Clearly, our results indicate that the *macMinBE* plays a key role in the achievable performance. Considering Equations 7.1 to 7.5 the term x_3 (*macMinBE*) enters with the positive sign. This suggests that to achieve better satisfaction rate, larger values should be chosen for this parameter. As a reminder, parameter determines the initial average waiting time after which a sensor node performs a carrier-sense operation for a new packet, so it is a measure for how aggressively a node tries to send data. Longer initial waiting times lead to fewer collisions so that more channel resources are left for useful transmissions even in high node densities.

[1]Here for $\delta = 250 WBSNs$ it is more than 78%

dynamic-phase-shifting	**WBSN = 50**	**WBSN = 100**	**WBSN = 150**	**WBSN = 200**	**WBSN = 250**
α_0 packet Success rate	93.4	92.6	89.8	87.3	82.1
standard deviation of packet loss rate	5.37	5.63	6.07	6.47	6.93

Table 7.5: Intercepts values for the success rate and its standard deviation for different number of WBSNs

7.4 Packet Success Rate

As mentioned previously, for applications which do not have a natural threshold it is interesting to look at their packet success rate performance. Table 7.5 shows the intercept value α_0 for the packet success rate and the standard deviation of the packet success rate for each $\delta \in \Delta$ related to DPS scheme.

While not shown here, the chosen second-order model has a very high R^2 value for all $\delta \in \Delta$. Therefore, it explains almost all of the observed variations. Moreover, the range of intercept values α_0 (considering all $\delta \in \Delta$) is relatively larger compared to the one for satisfaction rate. This again related suggests that introducing thresholds can make differences for different schemes.

Furthermore, to explore how fair the packet success rate allocation to WBSNs is, RSM analysis is carried out for the average standard deviations of the packet success rates. The intercept values for the standard deviation of the packet success rate is shown in Table 7.5. It can be observed that for all $\delta \in \Delta$ the average standard deviation does not exceed 7% which is considerably small compared to the average packet success rate percentage (shown in the same Table 7.5). This suggests that on average the differences in packet success rates among WBSNs are minor which again can be attributed to the fact that all WBSNs are configured in the same way.

7.5 Summary

This chapter is summarised in this section. In this chapter, we briefly explained the performance measures as a reminder: satisfaction rate, carrying capacity, energy consumption of both sensor and coordinator and orphan period. Then we introduced the static-idealized and static-random schemes as a hypothetical upper-band and lower-band of achievable performance (more particularly satisfaction rate), respectively. It was initially assumed that the static-idealized scheme in which WBSNs are evenly distributed over 16 available channels and equidistantly spread over time in each channel can minimise both holes in the channel and the overlapping ratio of WBSN‘s active periods compared to the static-random scheme in which WBSNs are uniformly distributed over 16 available channels only. Thereafter, significant gap between the hypothetical upper-band and the lower-band of the satisfaction rate has shown us the potential improvement of it.

The static-initial-choice scheme was then introduced in which a WBSN is able to select the channel with the smallest number of occupants only once and at the very beginning of its activation. The goal was to evenly distribute all WBSNs over 16 available channels at the initial stage and examine the satisfaction rate. The obtained results showed insignificant improvement of the satisfaction rate.

Thereafter, we examined the frequency adaptation strategy in which a WBSN is able to dynamically switch to other channels either randomly or by using the result of a measurement scheme. More precisely, in dynamic-random-hopping scheme, a WBSN is able to switch to a randomly selected channel when its success rate has degraded below the threshold. The significant improvement of satisfaction rate created the idea of switching to a channel with the smallest number of occupants instead of selecting the channel randomly. Therefore, the dynamic-targeted-hopping is designed and its performance was evaluated in comparison to the previously proposed schemes. Two approaches is offered for tracking down the channel with the smallest number of occupants: periodic-assessment and continuous-assessment. In the periodic-assessment, the coordinator of a WBSN starts to scan other channels immediately after the performance degradation, whereas in continuous-assessment the coordinator of a WBSN continuously scans the whole spectrum during its inactive period. The obtained results showed significant improvement of dynamic-targeted-hopping with continuous-assessment compared to the one with periodic-assessment in terms of satisfaction rate. However, the energy consumption of the dynamic-targeted-hopping with periodic-assessment is noticeably lower compared to the other one. Selecting the channel with the smallest number of occupants results in better resource allocation to WBSNs presumably due to almost evenly distribution of WBSNs over 16 available channel.

In the next stage, we analysed the sensitivity of satisfaction rate against the variation of several important system parameters: *beacon order*, *superframe order*, CSMA/CA parameters (*macMinBE* and *macMaxBE*) and the *system load*. For each system parameter the maximum and minimum values are considered and the deployment of response surface methodology has determined the most influential system parameter on the final performance gain. Additionally, we have realised that for static-idealized scheme offers higher satisfaction rate on average compared to dynamic-targeted-hopping scheme (second best passive scheme). This higher average of satisfaction rate for almost all 32 combinations of system parameter values can be attributed to the equidistantly spreading of the WBSNs over time within each and every channel. Therefore, in the next stage we have designed an active scheme called DPS scheme in which WBSNs are allowed to communicate with each other and share their views e.g. number of observed occupants. There are two main procedures offered by this scheme: frequency adaptation and phase adaptation. These two procedures allow a WBSN to shift the active phase to other time slot and at the same time find a channel with smallest number of occupants. The results showed significant improvement of the performance measured compared to other proposed schemes.

In the final stage we performed the sensitivity analysis of the previously-mentioned system parameters for the DPS scheme as well. The results suggest that *macMinBE* is by far the most influential factor on the performance of WBSNs. Additionally, by looking at the intercept values (α_0) of DPS scheme and compare it with the one in other schemes, it can be observed that DPS scheme, outperforms the considered passive schemes in terms of satisfaction rate.

8 Test-bed Performance Evaluation

This chapter explains the test-bed experiment and the implementation of the IEEE 802.15.4 MAC standard protocol and the DPS scheme described in Section 4.1.1 and 4.2, respectively. More specifically, this chapter provides a brief description of our deployed implementation elements and their specifications such as the operating system used for the experiments, the type of sensor nodes, the programming language to program sensor nodes and the considered scenarios including the number of wireless body sensor networks and their physical arrangements. We furthermore describe the experimental setup followed by the obtained measured results. In this thesis, the experimental study is conducted to explore the following main objectives:

- *To examine the feasibility of implementing the proposed phase-shifting algorithm on real-world sensor nodes.*
- *To qualitatively verify and confirm the performance trend of both static-random (IEEE 802.15.4 MAC standard protocol) and the DPS schemes[1] observed in our simulation study presented in section 7.1.*

[1] These two schemes are selected to be implemented on real-world sensor devices and not other schemes, mainly due to the following reasons: 1) The outcome of our simulation study showed that the DPS scheme (more particularly the dynamic phase shifting algorithm when WBSNs are utilising the same channel) outperforms all other schemes in terms of performance gains. 2) Since the static-random scheme closely represents the functionality of IEEE 802.15.4 standard MAC protocol (more specifically when WBSNs have not deployed neither of the frequency hopping nor phase-shifting), it is chosen as a baseline to compare its performance with the performance of DPS scheme.

8.1 Overview of Implementation

MicaZ motes [31] is the type of sensor nodes used in our experimental study. TKN154 [42] which is an implementation of the IEEE 802.15.4 MAC protocol under the TinyOS operating system (version 2.1.) [65] is used on MicaZ motes. The TKN154 has been developed and implemented using the *NesC* programming language.

TinyOS is a component-based operating system that is designed for embedding platforms. Interactions between components in TinyOS occur through interfaces. An interface itself has a *provider* and a *user*. Generally, the user of an interface calls the "commands" implemented by the provider and the interface provider signals the "events" to the interface user. More specifically, the interface provider calls the functions requested by the interface user.

The TKN154 is an implementation of the IEEE 802.15.4 protocol that comprises a set of components. These components interact with each other and with higher layers through previously-described interfaces. In our test-bed experiment, the implementation of the phase-shifting algorithm is placed into the application layer which is outside of the TKN154 components. This decision is made to leave the implementation of the TKN154 components untouched. In IEEE 802.15.4 standard MAC protocol the payload of the beacon packet can hold some necessary information. This facility is used in DPS scheme to inform the attached sensor devices (within a WBSN) about the next phase/time slot, and also to share views about the number of occupants in a channel for other coordinators. No other changes or modifications have occurred. In fact, leaving IEEE 802.15.4 MAC protocol unmodified (in both simulation and test-bed studies) is considered as one of the main achievements in this thesis. However, in order to implement the beacon-shifting algorithm on the real sensor devices, four major events are added to the TKN154 implementation. More specifically, an event is signalled at the sensor side to indicate the loss of beacon packet and eventually calculating the orphaning duration. Another event is signalled by the TKN154 MAC layer at the coordinator side to obtain critical information (e.g. number of detected beacon packets being sent by other coordinators) followed by signalling an event to update the own beacon packet using such information, and finally the last event is signalled at both sensor and coordinator nodes to take proper actions based on the obtained information.

- Signalling an event to indicate the loss of a beacon packet: This event is signalled at the sensor side and it indicates that the sensor was *unsuccessful* to receive a beacon packet transmitted from its associated coordinator. This event is signalled after passing a specific period of time called "Beacon Time Out". Please note that is event is previously designed and explained in [121].

- Signalling an event to force a coordinator to scan the channel: This event is signalled immediately after a coordinator has sent the beacon packet and forces the coordinator to stay awake for the whole beacon period and scan the currently-utilised operating frequency in order to detect as many beacon packets as possible. According to IEEE 802.15.4 standard, the coordinator of a WBSN switches to sleep mode after the CAP ends. However adding this event make the coordinator to remain switched on and continue scanning the channel during inactive period as well.

- Signalling the beacon-payload update: This event is signalled immediately before sending the next beacon beacon packet. When this event is signalled, the coordinator includes the detected number of beacon packets to its beacon payload.

- Signalling an event immediately before starting the next superframe: This event is signalled at both sensor and coordinator nodes immediately before starting the next superframe and provides them with the opportunity of changing their phase and resume their activity using a new time slot (phase) if required. Please note that is event is also previously designed and explained in

[121].

The above-mentioned events are added to the IEEE 802.15.4 MAC layer. The actual implementation of the DPS scheme is contained in the application compartment of the code. More specifically, when the channel-scan event is signalled at the coordinator, it listens to its current operating frequency for the period of a beacon period to detect as many beacons and possible and signalling the beacon-payload update event will update the information of the beacon payload.

8.2 Implementation in the nesC-TinyOS Environment

The NesC (Network embedded system C) programming language is used to implement the DPS scheme. This event-driven and component-based programming language is used on TinyOS operating system [42] which is an open source operating system being used to design schemes for distributed wireless sensor networks. A series of components are connected together and cooperate with each other in order to build and run an application for the TinyOS platform.

8.2.1 System Structure

Using component diagrams is one way to present the static system structure and the connections between different components within the system. Figures 8.1, 8.2, 8.3 and 8.4 show the system structure and the wired connections between the components for both the static-random and DPS schemes, for sensor and coordinator nodes, respectively.

The "MainC" component is triggered at the start-up and handles initialisation of the nodes, in both considered schemes. This component can be accessed through "boot" interface. "LedsC" is another component that uses the "leds" interface to con-

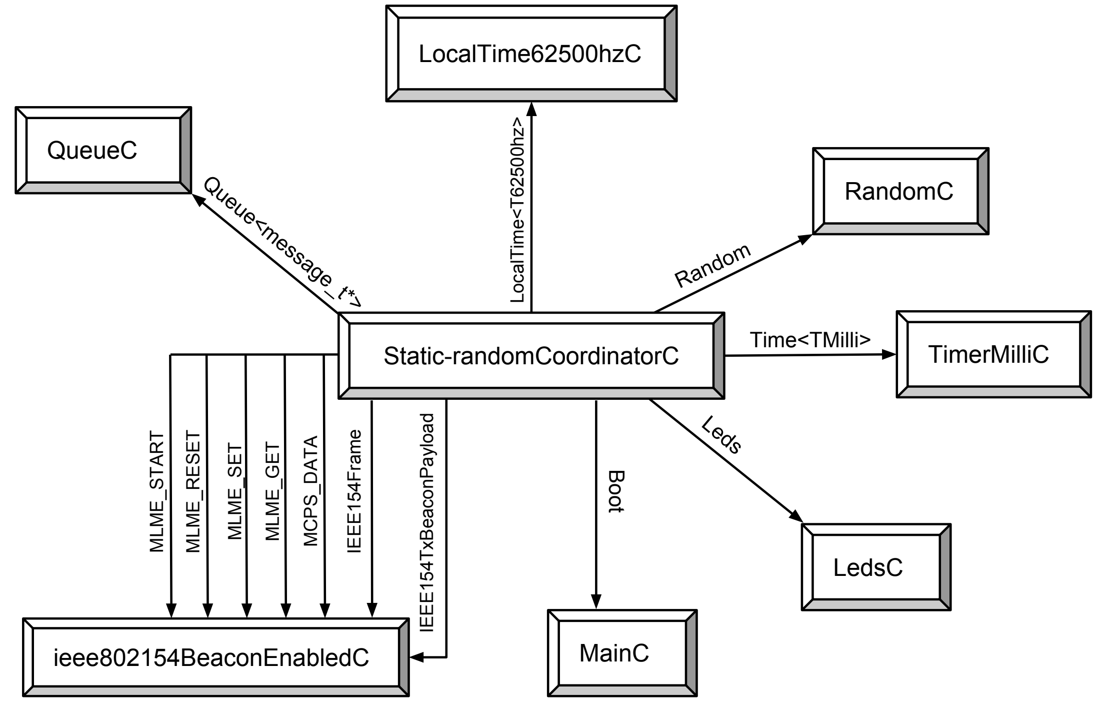


Figure 8.1: TinyOS structure for static-random scheme: coordinator side

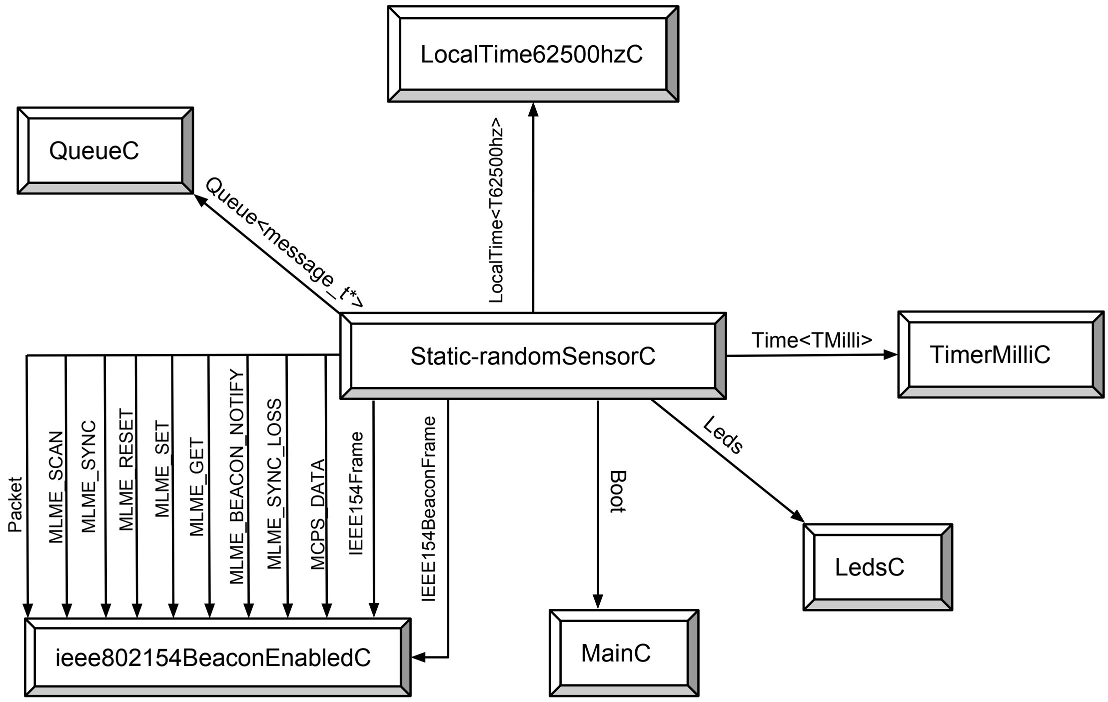


Figure 8.2: TinyOS structure for static-random scheme: sensor side

trol the LEDs embedded on a MicaZ device. The three coloured LEDs (Green,Yellow and Red) provide information related to the device status: sending and receiving

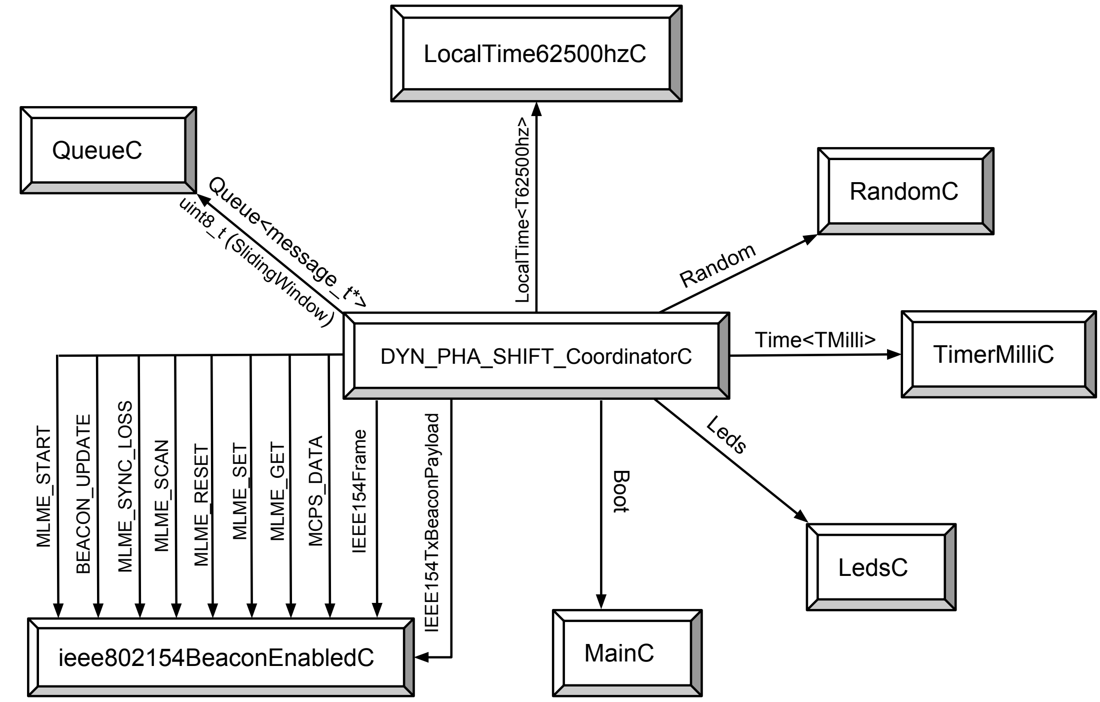


Figure 8.3: TinyOS structure for DPS scheme: coordinator side

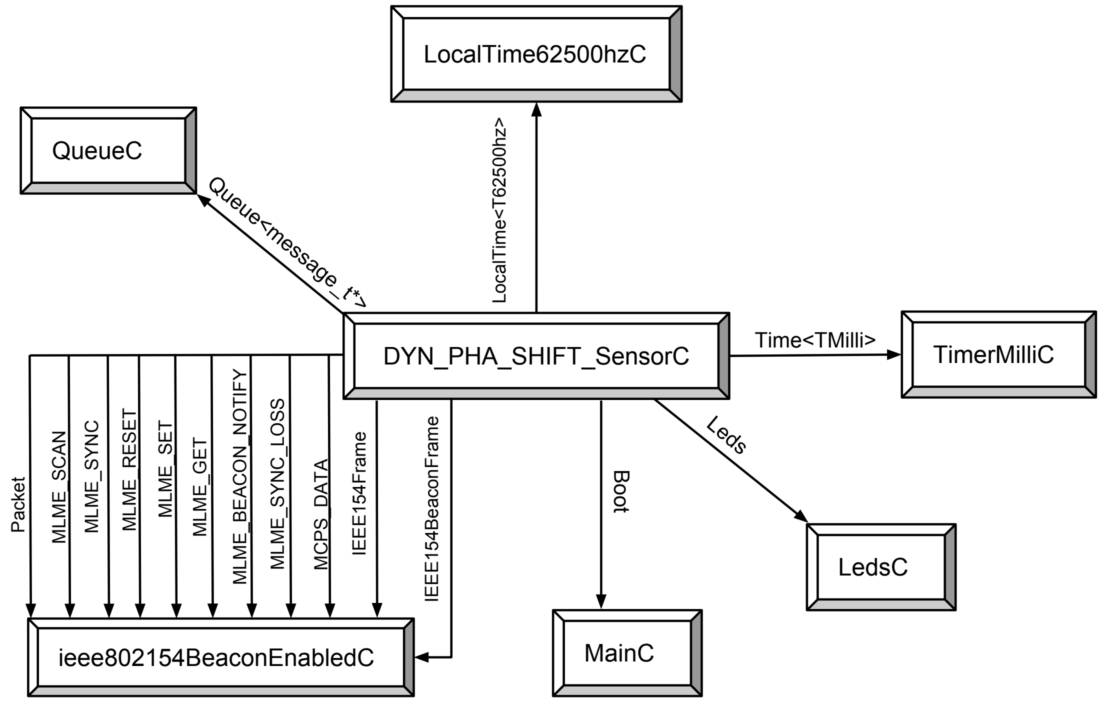


Figure 8.4: TinyOS structure for DPS scheme: sensor side

the beacon packets, sending and receiving the data packets, and whether the sensor device is associated to its corresponding coordinator or it has gone orphaned.

The "RandomC" component is used in coordinators to randomly pick a new phase (time slot) if required. The "TimerMilliC" and "QueueC" components are used to periodically debug and trace the activities within each wireless sensor networks.

It can be seen that the DPS scheme uses extra interfaces in the coordinator side: "MLME_SCAN" is used to collect as many other beacon packets as possible, "MLME_SYNC_LOSS" is used to receive a signal before the next superframe starts and "BEACON_UPDATE" is used to include the detected number of other beacon packets to the payload of the own beacon packet. Additionally, the "QueueC" is also used for packet loss estimation. MLME_GET and MLME_SET retrieve the necessary information (attribute values) from the MAC/PHY layer, or set those attribute values in the MAC/PHY layer, respectively. MLME_RESET resets the MAC sub-layer to its default values. MLME_SYNC defines a sensor device can synchronise with the coordinator and also how a loss of synchronisation is reported to the higher layers. MCPS_DATA requests the transfer of a data while setting some attribute values.

8.3 Experimental Setup

An experimental study is conducted to examine and explore the feasibility of implementing the DPS scheme on real sensor devices. Additionally, this study allows us to qualitatively verify and confirm the performance trends for the considered schemes (static-random and DPS schemes) obtained from our simulation study. In our experimental study, a wireless body sensor network consists of a sensor and a coordinator that are 1 m away from each other. In order to create the mutual interference situation, a number of δ WBSNs with $\delta \in \Delta = \{4, 7, 10, 14\}$ are equidistantly distributed on a circle with a radius of 1 m in such a way that the nodes of each individual WBSN are located at both ends of a diameter (opposite to each other on the circle). Using this particular arrangement allows wireless body sensor networks to be in each others coverage area and therefore the mutual interference can be experienced by each individual wireless body sensor networks. Furthermore, this arrangement allows us to eliminate the impact of hidden-terminals, path loss and different transmit power on the performance of WBSNs. Therefore, all packet collisions can be attributed to the mutual interference caused by neighbouring WBSNs. Please note that no external interference is considered or experienced in this study and the Figure 8.5 sketches the considered scenario when $\delta = 14$.

In order to rule out packet losses on the channel, we have used channel 26 where no external interference has been observed. To confirm this property multiple test-runs were carreid out using one sensor and one coordinator located 1m away from each other. The obtained results (0 packet loss) have suggested that the channel 26 is a reliable channel – in terms of not being exposed to external interference – when sensors and coordinators are 1m away from each other and the transmit power is -15 dbm. We have focused this study only on phase shifting functionality and have excluded frequency-hopping to study phase shifting in isolation and because of limited number of WBSNs. Therefore, all WBSNs are restricted to operate on one common operating frequency.

Figure 8.5: Wireless body sensor networks arrangement and information logging

The specification of the nodes considered for the experimental study is shown in Table 8.1:

Parameter	**Value**
Application Layer Parameters	
Data payload	64 byte
Coordinator start up delay	Manually at random times
MAC Layer (CC2420) Parameters	
Beacon Order	6
Superframe Order	4
MAC Buffer size	16
Max number of retransmissions	4
Packet validity time	$4 \times$ BI
Physical Layer (CC2420) Parameters	
Transmit power	-15 dBm
Data rate	250 kbps

Table 8.1: Experiment fixed parameters

8.3.1 Experimental Scenarios

In our experimental study two scenarios are considered:

Scenario 1: In this scenario, a number of WBSNs $\delta \in \Delta$ is considered (where $\Delta = \{4, 7, 10, 14\}$) and arranged in the form of a circle as explained before. We start to log the information after resetting all nodes. In this scenario, all WBSNs are active for 6000 seconds and the number of them is fixed throughout. For each $\delta \in \Delta$, we run the experiment 10 times and the final result is the average of each individual performance measure over all nodes of the same type (coordinators and sensors, respectively) and over all runs. We collected the performance data about the total number of beacon losses, orphan period, total number of transmission retries and total number of packet losses. Please note that all nodes will be reset after each experimental run.

Scenario 2: In this scenario the same physical arrangement of WBSNs is considered. However, the number of WBSNs is not fixed and varies over time. We start from $\delta = 14$ and the number of active WBSNs is decreased step-by-step down to $\delta = 4$ followed by increasing the number of active WBSNs up to $\delta = 14$. Each step represents a duration of *15 minutes = 900 seconds*. During each step the information regarding the performance of 5 coordinators and 4 sensors will be logged, and at the end of each step *a number of WBSNs* will be added or removed to and from the whole system according to the sequence $\{4, 7, 10, 14, 10, 7, 4\}$. A single run in this scenario will last for 105 minutes = 6400 seconds and a total of 10 runs are carried out. With this scenario, the behaviour of the DPS algorithm can be explored as the mutual interference changes over time. Moreover, this scenario allows us to determine the performance trends of both schemes (abrupt increase or decrease of the performance trend) as the number of WBSNs becomes slowly larger in a channel. Similar to the previous scenario, all nodes will be reset after each experimental run.

8.3.2 Performance Metrics

The following performance measures are considered to evaluate the performance of the considered schemes in our experimental study:

i) **Number of beacon packet loss**: This performance metric is obtained from the beacon packet sequence number and by counting the gaps between the sequence number of two consecutive received beacon packets at the sensor side. Finally, the average of the total number of lost beacon packets for the monitored sensor nodes and over all experimental runs is calculated.

ii) **Number of transmission retries**: When a sensor device does not receive the acknowledgement packet associated with the most recently data packet, it attempts to retransmit that data packet up to four times and drop it from the data transmission-queue thereafter. The number of transmission retries is considered as one of the metrics that is helpful to understand the data packet collision experienced at the different intensity-levels of the mutual interference. This performance metric is also collected at the sensor side and is the average of the total number of transmission retries which occurred for the monitored sensor nodes and over all experimental runs.

iii) **Duration of time spent in orphan state**: When a sensor node does not receive four consecutive beacon packets from its associated coordinator, it goes to the orphan state. This performance metric is used to further clarify the impact of the mutual interference on packet collisions (beacon packets) and eventually the duration of time that a sensor node has spent in the orphan state. This performance metric is also calculated at the sensor side and is the average of the total amount of time spent in orphan state for the monitored sensor nodes and over all experimental runs. Please note that when a sensor node becomes orphan, it only scans its current channel. This is mainly due to the fact that we have utilised one channel for our experimental study. This means that in real life experiences this time will be longer as sensor devices should scan larger number of channels to find their coordinators.

iv) **Number of data packet loss**: This performance metric is calculated at the coordinator side and is obtained from the data packet sequence numbers and by counting the gap between the sequence number of the consecutive received data packets. Finally, the average of the total lost data packets for the monitored coordinator nodes and over all experimental runs is calculated as the number of lost data packet.

v) **Number of time slot shifts**: This performance metric is specific to the DPS scheme, in which WBSNs are able to communicate with each other and shift their phases if required. The number of shifts is calculated by counting them at the coordinator side. Then the average of the total number of shifts for the monitored coordinators and over all experimental runs is considered as the number of time slot shifts.

vi) **Duration of time Spent in unsettled state**: This performance metric also helps to have a better understanding of the DPS scheme. Considering the Figure 4.7 that presents the state machine diagram for the DPS scheme, when the success rate degrades below the satisfaction threshold, the wireless body sensor network transits to the unsettled state in which the coordinator randomly selects a time slot. After informing the associated sensor node, the sensor network resumes its activities in the newly selected time slot. This performance metric is also the average of the total amount of time spent in unsettled state for all coordinator nodes and over all experimental runs.

8.4 Results

The results obtained from our experimental study are presented in this section. As a reminder, this study considers the static-random scheme (which represents the IEEE 802.15.4 standard MAC protocol) and the DPS scheme which, in our simulation study, achieved the highest reliability of data packet transmission amongst the other considered schemes in this thesis. Each of the two schemes is considered in two scenarios: in the first scenario presented in Section 8.4.1, for each δ (number of WBSNs where $\delta \in \Delta$ and $\Delta = \{4, 7, 10, 14\}$), 10 experimental runs were carried out. In the second scenario, the δ sensor networks is varied overtime in an individual experimental run in Section 8.4.2. The second scenario is also repeated 10 times. Due to equipment limitations encountered in our experimental study (mainly: small number of programming[2] boards), the results of only five coordinators and four associated sensors were obtained at a time and the remaining of WBSNs were responsible to create the mutual interference. In each experimental run the average of the previously-mentioned performance measures of five coordinators and four as-

[2]The statistical information associated to a node is collected by attaching that node to the MIB250 programming board that itself is connected to a laptop

sociated sensors are obtained. Finally, the presented graphs show the results of the average of the performance measures over 10 experimental runs.

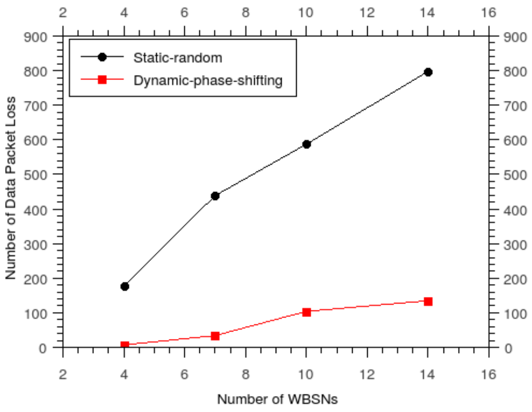
8.4.1 First Scenario

The obtained results from the first scenario are shown in Figure 8.6. Please note that the experimental results are not directly comparable with the ones obtained from the simulation study due to the above-mentioned limitations. Considering Figure 8.6a, the huge gap between the average number of lost data packet between both schemes explains the significant improvement of the transmission reliability offered by the DPS algorithm. Moreover, it is also interesting to see that as the number of WBSNs becomes larger not only the absolute levels are high but also the the growth is faster for the static-random scheme compared to the DPS scheme where the transmission of the data packets has gracefully degraded. This is mostly due to the ability of shifting the beacon packet and the subsequent active period to another time slot/phase (when the packet success rate degrades below the satisfaction threshold) performed by the DPS scheme.

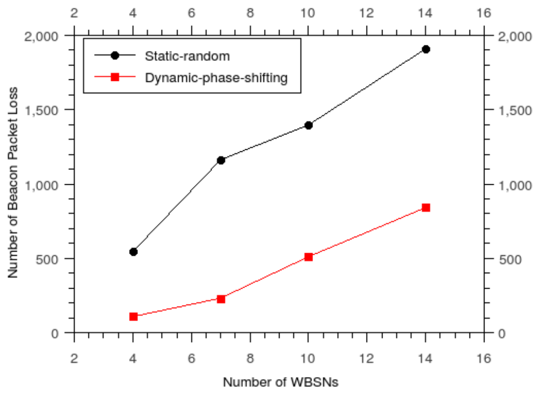
The amount of time spent in the orphan state is important since it has been shown in our simulation-based study that the sensor energy consumption is directly related to this amount of time. Figures 8.6b and 8.6c show significant gaps in terms of number of lost beacon packets and the duration of time spent in the orphan state, respectively. It is interesting to see that while these Figures both show similar upward trends, the created gap in the graph presenting the number of beacon packet loss is larger compared to the gap in the graph presenting the duration of time spent in orphan state. This suggests that as the number of wireless body sensor networks becomes larger in a channel, a noticeable number of beacon packets is lost *purely* due to packet collisions and *not* because the sensor node was missing beacon packets due to being in orphan state. Please note that beacon packets are transmitted without performing the CCA procedure. Clearly, the DPS scheme outperforms the static-random scheme in terms of both number of beacon packet loss and the amount of time spent in orphan state. This is again mainly due to the ability of shifting the beacon packet and the subsequent active period to another phase which helps sensor nodes to maintain their connectivity to the associated coordinator. As a result, a smaller number of beacon packet is lost and consequently less time is spent in orphan state.

The transmission re-tries occur when a sensor node does not receive the acknowledgement packet related to the last data packet. This is also considered as a helpful performance measure representing the amount of packet collisions caused by mutual interference. Figure 8.6d illustrates the average number of transmission re-tries for both considered schemes. Similar to the previous graphs, as the number of WBSNs increases, the probability of experiencing mutual interference will be increased. As a result, more data packet and/or acknowledgement packet will collide with each other, and a larger number of transmission re-tries will be experienced. Please note that similar to beacon packets, acknowledgement packets are sent without performing the CCA procedure which makes acknowledgement packets more vulnerable to collision, with themselves or other types of packets. Clearly, the DPS scheme outperforms the static-random scheme in terms of having a smaller number of transmission re-tries due to the ability of shifting the beacon to another time slot/phase and moving away from the experienced mutual interference.

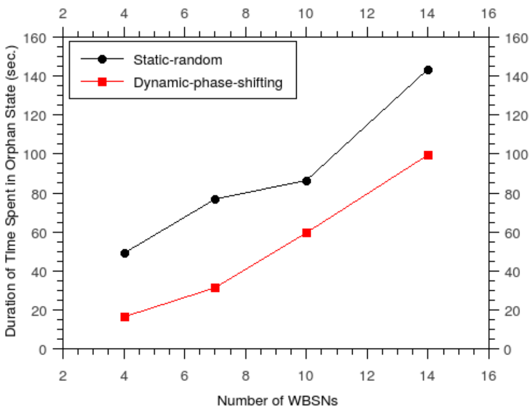
The last two Figures in this subsection are related to the number of phase-shifts that (on average) a WBSN carries out to keep its sensor node as satisfied as possible, and the duration of time that (on average) it actually spends in the unsettled state looking for a new suitable time slot/phase. Figures 8.6e and 8.6f illustrate the average number of phase shifts and the average amount of time that a wireless sensor network spent in unsettled state, respectively. The results show a wide range of numbers of phase shifts from less than 5 phase-shifts (when there were only four WBSNs) to approximately 38 phase-shifts (when there were 14 WBSNs in a



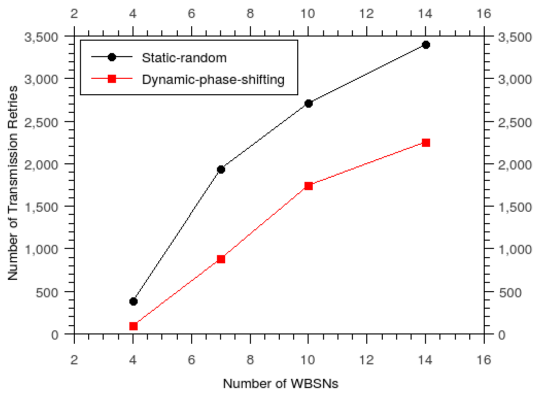
(a) Average number of data packet loss



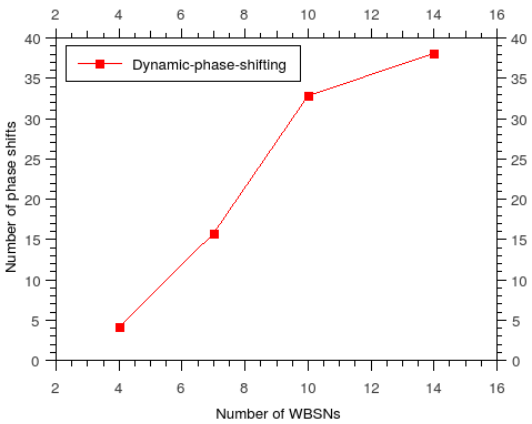
(b) Average number of beacon packet loss



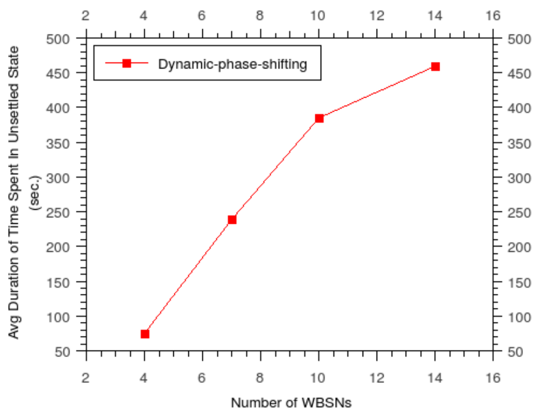
(c) Average duration of time spent in orphan state



(d) Average number of transmission re-tries



(e) Average number of phase shifts



(f) Average amount of time spent in unsettled state

Figure 8.6: First Scenario: the performance evaluation of DPS and static-random schemes

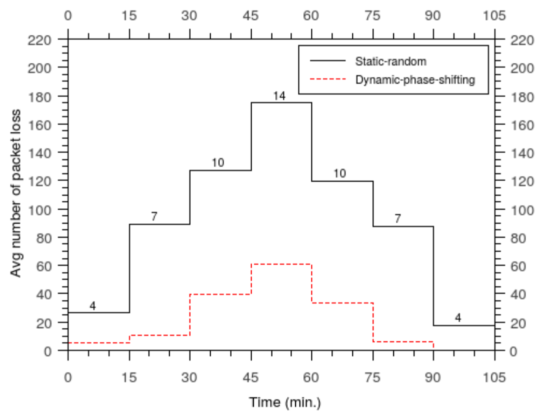
channel). Similarly, there is an increase from 70 seconds (on average) spent in unsettled state up to 470 seconds for the same range of number of WBSNs. When the number of WBSNs becomes larger in a channel, more time will be spent in the unsettled state and more phase-shifts will be required to keep the network as satisfied as possible.

8.4.2 Second Scenario

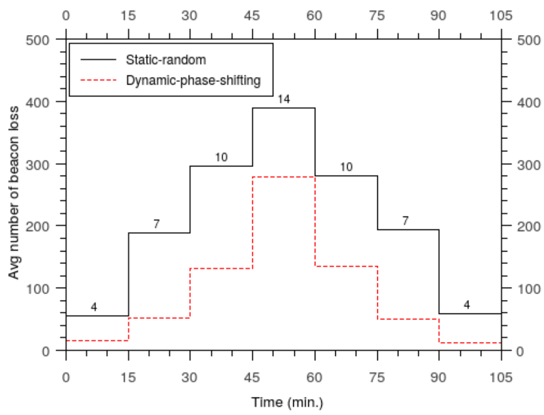
In the second scenario, the performance of both schemes is examined for varying intensity of mutual interference. More specifically, in each experimental run, the number δ WBSNs is varied step-by-step according to $\delta = 4, 7, 10, 14, 10, 7, 4$. Each step lasts for 15 minutes. In each step, the information related to the same performance measures as for the first scenario are collected. Figure 8.7 illustrates the performance trends of both schemes over time. Clearly, mutual interference significantly impacts all performance measures. As the number of WBSNs becomes larger in a channel more data packets will collide with each other, fewer beacon packets will be received, more time will be spent in orphan state, and a larger number of transmission re-tries will be required.

Figure 8.7a shows the average number of lost data packets over time for both schemes. As the number of WBSNs increases, a larger portion of active periods will overlap on each other. This results in experiencing more packet collisions. However, phase-shifting algorithm allows WBSNs to shift their beacon packets to another time slot/phase whenever their successful transmission of the data packets degraded below the satisfaction threshold. Clearly, using this strategy has significantly decreased the number of lost data packets compared to static-random scheme.

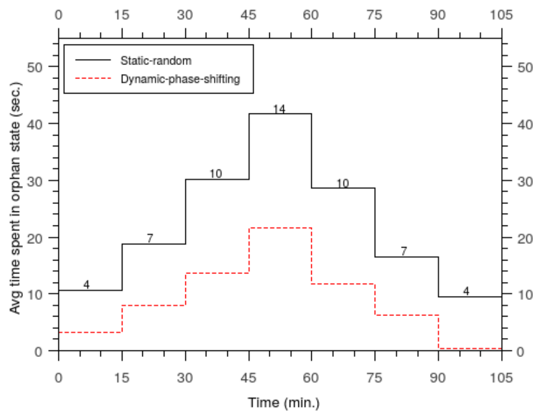
The average number of lost beacon packets as well as the average duration of time spent in the orphan state are illustrated in Figures 8.7b and 8.7c, respectively.



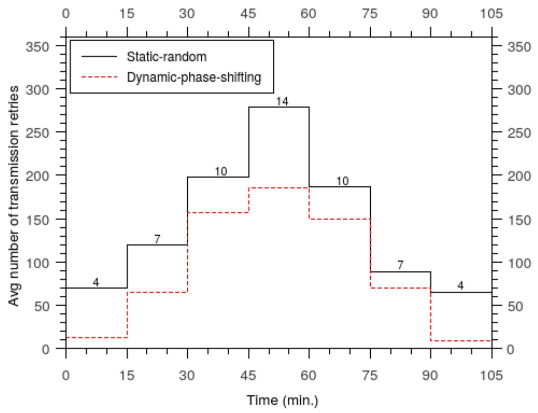
(a) Average number of data packet loss over time



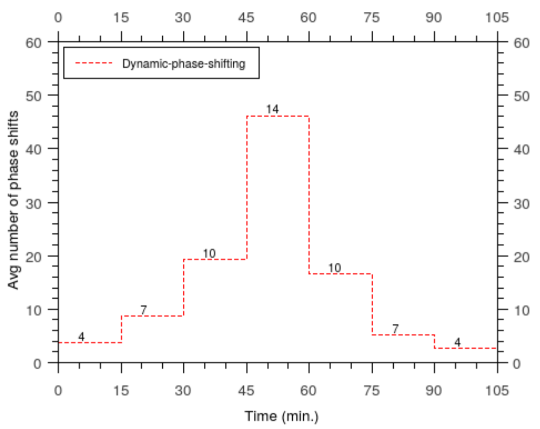
(b) Average number of beacon packet loss over time



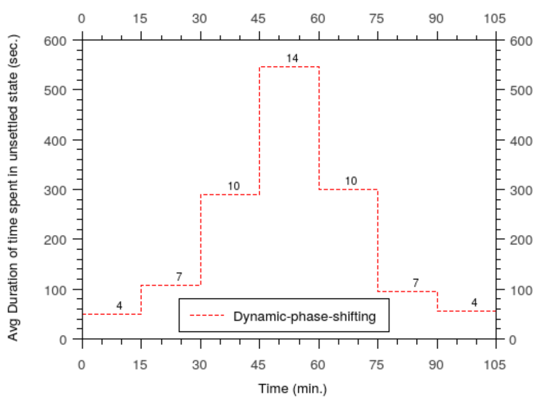
(c) Average duration of time spent in orphan state over time



(d) Average number of transmission re-tries over time



(e) Average number of phase shifts over time



(f) Average amount of time spent in unsettled state over time

Figure 8.7: Second Scenario: the performance evaluation of DPS and static-random schemes over time

Similar to the first scenario, these graphs show the noticeable gaps between the performance of the considered schemes in terms of lost beacon packets and the orphan time. As the number of WBSNs becomes larger in a channel the probability of packet collisions will be increased. Since beacon packets are transmitted without performing the CCA procedure, higher packet collisions result larger number of lost beacon packets and increased chances of becoming an orphan. Moreover, as the number of WBSNs is varied (according to $\delta = 4, 7, 10, 14, 10, 7, 4$), both schemes show gradual changes over time and no sudden jumps is encountered. Clearly, the ability of shifting the beacon packet to other time slots/phases, has decreased the average number of lost beacon packets and the time spent in orphan state. Additionally, it is interesting to analyse the size of the gaps between the performance measures of both schemes in each step. As the δ increases, the size of the gap for the number of lost data packets, number of lost beacon packets, and the orphaning time (mostly) becomes larger and conversely, as the δ decreases the size of the gaps becomes smaller.

Figure 8.7d also shows the increase and decrease of the average number of transmission re-tries as the number of wireless sensor networks becomes larger and smaller. The results show that there is a noticeable gap between the average number of transmission re-tries presented by both schemes. Again both schemes show gradual changes over time and no sudden changes is observed. The size of the gaps associated to each step, however, do not gradually become smaller as the number of WBSNs becomes smaller. In other words, a statistical variation can be seen from level differences for the same δ and is associated to the number of extra runs required o resolve this discrepancy[3].

Figures 8.7e and 8.7f show the average number of phase-shifts and the average duration of time spent in unsettled state, respectively. It is interesting to see as the number of WBSNs increases, the duration of time spent in unsettled state increases,

[3]Due to time frame limitation of possessing the equipments, conducting extra experimental runs was not possible.

noticeably. This explains the fact that larger number of WBSNs experience more performance degradation due to packet collisions. Furthermore, will be spent in the unsettled state to find another time slot/phase.

8.5 Verification Of Objectives

Finally, here in this section we explicitly discuss the outcomes for the objectives mentioned at the beginning of this chapter. The obtained results show that it is feasible to implement the phase-shifting algorithm on real-world sensor nodes without incurring any modifications to the IEEE 802.15.4 protocol, and also the performance of DPS and static-random schemes is qualitatively confirmed.

8.6 Summary

The performance of IEEE 802.15.4 standard MAC protocol is compared (in a single channel) against the DPS scheme in which a WBSNs is enable to dynamically shift its beacon and the subsequent active period to another phase. The DPS algorithm allows WBSNs to reduce the percentage of overlapping ratio of active periods. Consequently, lower data and beacon packets will be lost due to packet collisions which results in smaller number of transmission re-tries and shorter orphaning time, respectively. Two scenarios have been considered to explore the performance of static-random scheme – in our case representing IEEE 802.15.4 standard MAC protocol – and the DPS scheme. In each scenario, a number of performance measures was used to evaluate their performance. The obtained results show that dynamic-phase shifting scheme can significantly improve the performance gain of IEEE 802.15.4 standard MAC protocol in terms of reliability of packet transmission.

9 Conclusions

In this thesis the internal/mutual interference caused by neighbouring WBSNs has been introduced and its influence on the performance of WBSNs has been investigated. More precisely, the impact of mutual interference on reliable data transmission between a sensor node and its coordinator node has been analysed and the impact of such interference on the overall energy consumption of the network has been explored. An extensive simulation-based study was carried out in which a number of schemes were proposed to improve the reliability of data transmission as well as the overall energy consumption of the sensor nodes in the presence of mutual interference. In particular we have proposed **Adaptive Resource Allocation** schemes, in which WBSNs are able to adaptively change their operating frequency and/or their active phases (time slots) to better utilise the available channels (resources). Finally, the scheme with the comparatively best performance gain has been chosen for implementation on real-world sensor nodes, not only to ensure the feasibility of embedding and implementing such scheme on commercially available sensor nodes, but also to provide a statistic comparison between the performance obtained by our proposed scheme and the IEEE 802.15.4 standardised MAC protocol.

9.1 Results and Findings

A summary of the obtained results from both simulation-based and experimental studies is as follows:

- A simulation-based study has been conducted to compare the performance of the static-random scheme and the static-idealized scheme. The obtained results has shown a significantly large gap in terms of their performance gains.

- The **static-initial-choice** scheme (in which WBSNs are given the opportunity of selecting a channel with the smallest number of occupants only once after activation) has only shown a slight performance improvement.

- The **dynamic-random-hopping** scheme (in which WBSNs are able to switch to a randomly chosen operating frequency) showed noticeable performance improvement. However, there was still a significant gap between the dynamic-random-hopping scheme and the static-idealized scheme.

- The **dynamic-targeted-hopping with periodic assessment** scheme (in which WBSNs periodically assess their success rate and start scanning the frequency spectrum to find a new suitable channel if required) showed only a slight improvements compared to the dynamic-random-hopping scheme.

- In the dynamic-targeted-hopping with periodic assessment scheme, the coordinator of a WBSN periodically (every 50 beacon intervals) assesses the quality of the channel (calculating the own packet loss rate) and starts to scan the frequency spectrum when it realises that the success rate has dropped below the threshold. In this scheme, the coordinator of a WBSN might not notice the exact moment that the success rate has dropped below the threshold. Therefore, another dynamic-targeted scheme is designed in which .

  This scheme is called **dynamic-targeted-hopping with continuous assessment** scheme (in which the coordinator of a wireless sensor networks not only assesses the quality of the channel in every superframe, but also it continuously scans the available operating frequencies in order to keep track of the channel with the smallest number of occupants) results in a better distribution of the WSBNs over 16 available channels. The obtained results have shown that the higher energy consumption of the coordinator is compensated by a noticeable improvement of the reliability of the data packet transmission and sensor energy consumption. However, there is still a gap to static-idealized scheme, which we attribute to the lack of phase shifting.

- The response surface methodology has been used to determine the influence of a set of system parameter variations on the satisfaction rate of WBSNs. The results have shown that macMinBE and macMaxBE are respectively the first and the second dominant factors that have comparatively higher influence on the satisfaction rate. Moreover, this study analyses the *behaviour* of the proposed considered schemes over the variation of the different system parameter values: it suggests that in the scheme where WBSNs are evenly distributed over 16 available channels and equidistantly-distributed over time within each channel (static-idealized), the highest satisfaction rate can be obtained for almost all combinations of the different system parameters values. The second best proposed scheme is the dynamic-targeted-hopping with continuous assessment in which WBSNs which offers better distribution of WBSNs over 16 available channels compared to dynamic-random-hopping and static-random schemes.

- The obtained results from the RSM study have highlighted the need to design a scheme where WBSNs are able to change their phases (shift their beacon to another time slot), if required. Therefore, we have designed the **DPS** scheme in which WBSNs are able to share their views about the number of occupants of the current channel to better utilise the current and other channels in the frequency band. The obtained results show the highest satisfaction rate compared to the rest of the proposed schemes. It is worth mentioning that in this scheme a WBSN uses its beacon packet (which is accessible by other wireless body sensor networks) to pass information to others and no extra packet (e.g.

command packet) is used.

- The RSM is also applied to the DPS scheme and the results show that the DPS scheme achieves the highest average satisfaction rate compared to static-idealized and – by extension – the dynamic-targeted-hopping schemes. In this scheme, the *macMinBE* is also the dominant factor in terms of the highest influence on the satisfaction rate.

- Finally, two sets of experimental studies have been carried out to determine the feasibility of implementing the DPS scheme and to compare it to the static-random scheme. The results obtained from both sets of experiment show that the DPS scheme significantly outperforms the static-random scheme in terms of data packet loss, beacon packet loss, fraction of time spent in orphan state and the transmission re-tries.

9.2 Evaluation of The Hypotheses

here we discuss the hypotheses stated in Section 1.5, using the results obtained from both simulation- and experimentation-based studies:

Hypothesis 1:

(a) As the number of WBSNs becomes larger and the mutual interference becomes more intense, an adaptive frequency hopping strategy (either randomly or using measurements) allows a WSBN to switch to the channel with the smallest number of occupants. Although utilising a frequency adaptation strategy could cause higher energy consumption (particularly for the coordinator node) and also would increase the risk of node orphaning, it is expected that the primary performance measures would be improved noticeably.

(b) In the environment where WBSNs experience performance degradation due to mutual interference, adaptive frequency hopping strategy and switching to the channel with the smallest number of occupants, **can** be an effective way to improve the reliability of the data packet transmission between a sensor node and its associated coordinator node, despite the higher energy consumption of coordinator nodes and higher risk of sensor node orphaning.

Hypothesis 2

(a) By preforming the sensitivity analysis of the satisfaction rate against the variation of a candidate set of system parameter configurations the most influential factors on the WBSN performance will be determined. This information is useful for the future adaptation of the system parameters. Moreover, it is expected to see that, for a range of system parameter variations, equal allocation of frequency spectrum (equal distribution of WBSNs over all available channels and equi-distantly spreading them over time) to all WBSNs will result in higher network performance compared to the frequency adaptation alone.

(b) The results obtained from the sensitivity analysis of the satisfaction rate against the variation of a candidate set of system parameter configurations has not only highlighted the most influential factors on the WBSN performance, but also it has shown that equal allocation of resources (equal distribution of WSBNs over all available channels and time slots within each channel) results in higher network performance compared to the frequency adaptation alone.

Hypothesis 3

(a) By introducing the adaptive phase-shifting strategy and coupling it with the adaptive frequency hopping strategy significant improvement of network performance could be achieved, compared to frequency adaptation alone.

(b) Coupling the *adaptive frequency hopping* strategy with the *adaptive phase shifting* strategy in the environment where WBSNs experience performance degradation due to mutual interference, again despite the higher coordinator node's energy consumption as well as higher risk of sensor node orphaning, **can** be considered as another effective solution to increase the reliability of the data packet transmission between a sensor node and its associated coordinator node even more.

Hypothesis 4

(a) The phase-shifting strategy can be designed in such a way that it can be fully compatible with the current commercialised sensor devices and no modifications or changes to the IEEE 802.15.4 standard MAC will be required.

(b) Phase-shifting algorithm has been implemented on the real-world sensor device and its performance is compared against the IEEE 802.15.4 standard MAC. Therefore, the feasibility of its implementation is also verified.

9.3 Future Works

This thesis offers a number of possible future explorations; some of them are briefly suggested as follows:

- In this thesis we have considered the situations where WBSNs are stationary and not able to move around. Therefore, investigating the impact of mutual interference in the presence of mobility and hidden-terminal scenarios can be interesting future works.

- In this thesis we have assumed that a WBSN is configured in a one-hop star topology. It would be interesting to examine the performance of the proposed schemes in multi-hop networks and explore possible improvements if required.

- In this thesis, the impact of transmit power has been ruled out by locating all WBSNs in each other's coverage area. It is also interesting to explore the benefits/disadvantages of the adaptive transmit power schemes in the presence of mutual interference.

- It is also interesting to see how the proposed DPS scheme could be added to the IEEE 802.15.6 and if similar outcomes (as illustrated in this thesis) could be achieved.

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